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THE EFFECTS OF SUPERSATURATION OF DISSOLVED GASES ON THE FISHERY OF THE BIGHORN RIVER DOWNSTREAM OF THE YELLOWTAIL AFTERBAY DAM.

1987 Annual Report
June 1988

Prepared for:
U. S. Department of the Interior
Bureau of Reclamation
Missouri Basin
Region 6

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INTRODUCTION

Several excellent literature reviews describing problems associated with gas supersaturation in natural waters have recently been published (Bouck 1980; Weitkamp and Katz 1980; Colt et al. 1986); thus there is little need to review the gas bubble trauma literature here. Bouck (1980) describes gas bubble trauma (GBT) as a "physically induced process caused by uncompensated hyperbaric pressure of total dissolved gases." Gas bubble trauma has commonly been documented in fish living below dams where plunging water entraps atmospheric gases and forces them to a depth where they become supersaturated (Bouck 1980).

Symptoms of the trauma in fish include formation of emboli in blood vessels and emphysema in soft tissues. Fish exposed to supersaturated gases commonly form bubbles in fins, on the opercles or in the oral cavity. In severe cases, fish may develop exophthalmia or pop-eye (Weitkamp and Katz 1980). All of these symptoms have been observed in fish from the Bighorn River downstream of the Yellowtail Afterbay Dam.

The Yellowtail Afterbay Dam serves as a reregulating facility below Yellowtail Dam and powerplant to provide uniform daily discharges into the Bighorn River. The presence of gas bubble trauma (GBT) in trout below the Afterbay Dam was first documented in 1973 (Swedberg 1973). The Bureau of Reclamation and Montana Department of Fish, Wildlife and Parks (MDFWP) subsequently concluded that gas entrainment occurs when water passes through gates in the Afterbay Dam, particularly the sluiceway gates (Bureau of Reclamation 1973). However, they surmised that no practical modifications in the Afterbay operation would preclude gas levels from exceeding 110% saturation, the present Environmental Protection Agency (EPA) criterion for total dissolved gases to protect freshwater aquatic life (EPA 1976).

A fish kill observed in 1979 was allegedly due to gas bubble trauma (Porter and Viel 1980). Subsequent studies by the U. S. Fish and Wildlife Service demonstrated the geographic extent and biological severity of the problem. From February-August 1981, 33 and 11% of the brown and rainbow trout, respectively, exhibited external symptoms of GBT (Curry and Curry 1981). Gas bubble trauma in brown trout during 1981 peaked in June when 72% of those captured were affected (Curry and Curry 1981). Also most (90%) of the traumatized fish were found in the first 8 river kilometers (5 river miles) below Afterbay dam (Porter and Viel 1980).

In fall 1982, the Bureau of Reclamation attempted to solve the problem by installing deflector plates (flip lips) on the face of the dam. However, turbulence resulting from these structures caused rocks to be pulled into the afterbay stilling basin and threatened to erode the base of the dam; because of this they were removed in July 1983.

More recent monitoring by the MDFWP confirms that the problem persists and that large brown trout, those $\geq$ 356 mm (14.0 inches), are the most visibly affected segment of the population and that brown trout are more susceptible than rainbow trout.

Additionally, the lack of successful rainbow trout reproduction in the mainstem Bighorn River may be due to the gas problem (Fredenberg 1985). It is clear from work conducted to date that we do not fully understand the relationships between reservoir operations, flows and other ambient conditions on gas supersaturation levels and the incidence of gas bubble trauma in fishes. Furthermore, we do not know why adult brown trout exhibit more severe external symptoms of gas bubble trauma than adult rainbow trout nor why rainbow trout reproduction appears suppressed. The Bighorn River, because of its relatively small size compared to other western hydroelectric projects where gas supersaturation problems exist (e.g., the Columbia River), presents an acceptable study site for increasing our understanding of the relationships between operation and design of dams and gas bubble trauma. Accordingly, this study was undertaken to:

(1) relate fish population levels and seasonal mortality to gas bubble incidence and dissolved gas saturation regimes.

(2) determine survival rates and factors controlling survival of early life history stages of brown and rainbow trout in the Bighorn River.

(3) relate gas bubble trauma incidence to ambient conditions including gas saturation levels, flow rates and reservoir operation.

(4) determine if different species or life stages of trout partition themselves in the environment in such a way as to influence their susceptibility to gas supersaturation.

(5) determine the catchability of traumatized vs. healthy fish in order to assess the impact of gas bubble disease on the fishing public.

(6) in a more controlled setting, examine incidence of occurrence of gas bubble trauma for various life stages and species at varying water depths and for different river reaches.

(7) determine the ability of brown trout to recover from gas bubble trauma after acquiring symptoms of varying degrees of severity and to assess the influence of water temperature on rate of recovery.

(8) determine what mechanisms (physiological or otherwise) result in brown trout having a higher incidence of gas bubble trauma than rainbow trout in the Bighorn River and to determine what dissolved gas saturation levels are safe for each of these species.

(9) assess the impacts of gas supersaturation on invertebrates and forage fish in the Bighorn River.

Information presented in this report was collected between 1 January and 31 December, 1987 and relates to all the above objectives.

DESCRIPTION OF STUDY AREA

Yellowtail and Afterbay Dams are located in south-central Montana on the Bighorn River approximately 43 air miles southeast of Billings on the Crow Indian Reservation. The facility was constructed from 1963-1966 (WPRS 1980). The principal uses of Yellowtail include power generation, irrigation, flood control and fish and wildlife enhancement. A 250-MW peaking plant is located at the base of Yellowtail Dam. This thin-arch concrete structure is 160 m (525 ft) high and 442 m (1,450 ft) long at the crest. Afterbay Dam, which serves as a reregulating facility, is located 3.5 km (2.2 miles) downstream of the main dam; it is an earthfill embankment with concrete spillway, sluiceway and diversion works. The height of Afterbay Dam is 22 m (72 ft) and it has an overall crest length of 414.5 m (1,360 ft). The spillway has a discharge capacity of 566.4 m^3/s (20,000 cfs), and is 49.4 m (162 ft) wide; flows are controlled by five, 9.1 m x 4.1 m (30x13.5 ft) radial gates and by the sluiceway, which is 10.4 m (34 ft) wide; its discharge is adjusted by three, 3x2.4 m (10x8 ft) slide gates. The height from the streambed to the maximum controlled water surface is 16.1 m (53 ft). The sluiceway gates can release water 6.9 m (22.5 ft) lower than the radial gates. Flow is continually adjusted, usually by the automated sluiceway slide gates, to maintain a relatively uniform flow to the river.

The study area extends approximately 19.3 km (12 miles) downstream of Afterbay Dam to Bighorn Access (Figure 1). The gradient is approximately 1.9 m per river kilometer (6.3

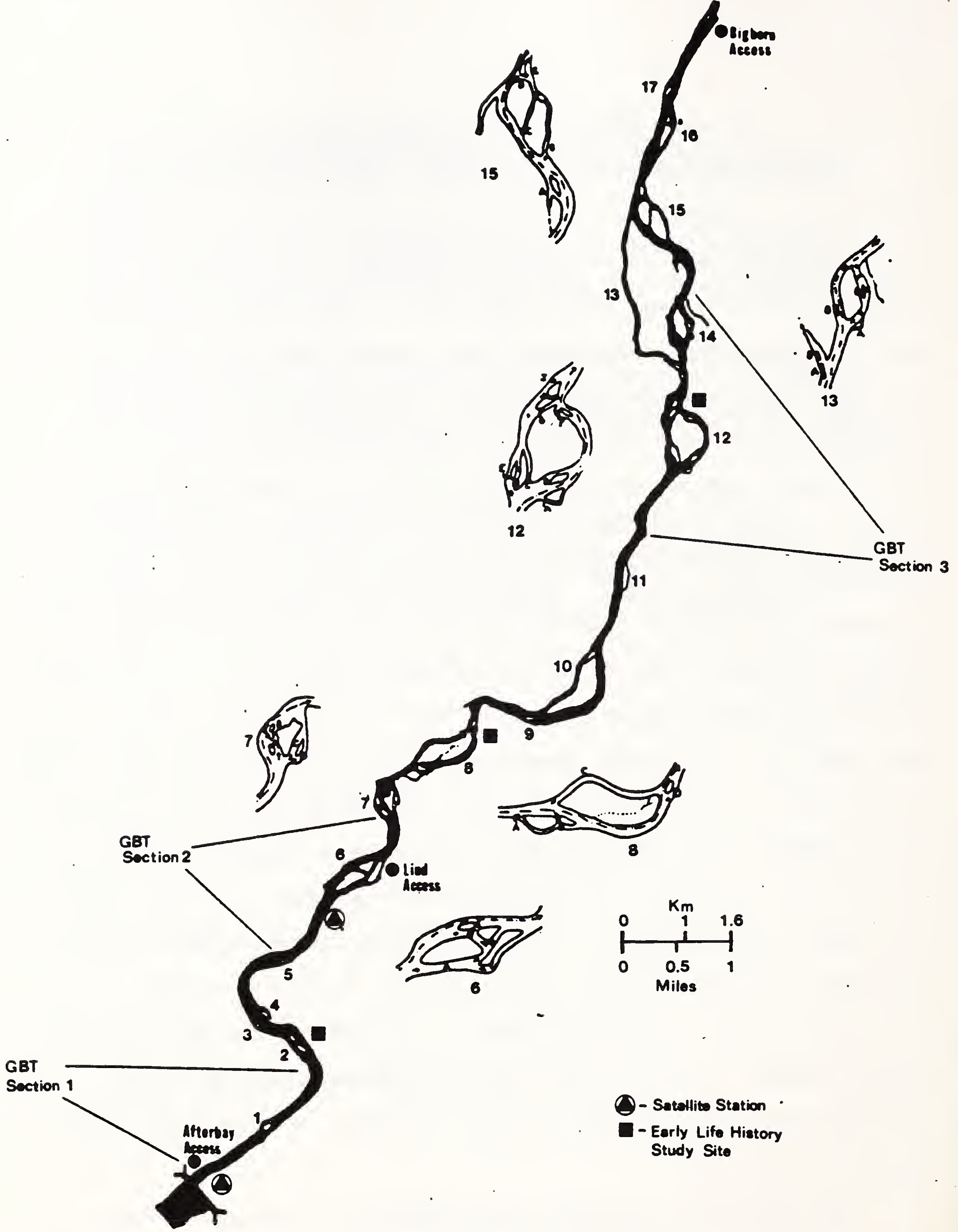


Figure 1. Map of the study area showing GBT electrofishing sections, early life history study sites, satellite relay stations, side-channel index and access sites.

feet/river mile) (Stevenson 1975) and the river channel braids in several areas, forming numerous islands. The riverbottom is dominated throughout this length by cottonwoods. Public access sites are located immediately downstream of the Afterbay Dam, at Rkm 5.4 (RM 3.4; Lind Access) and at Rkm 19.3 (RM 12.0; Bighorn Access). The largest tributary that enters the river within the study area is Soap Creek; its mouth is about 15.6 Rkm (9.7 RM) downstream of Afterbay Dam.

Electrofishing sections were established to obtain population estimates in the study area; one extends from the Afterbay to Rkm 3.9 (RM 2.4) and another from Rkm 3.9-15.4 (RM 2.4-9.6), the latter being one of MDFWP's established sections for fish population estimates. Additional subsections were established within the electrofishing sections at Rkm 0-1.9 (RM 0-1.2), Rkm 3.9-6.1 (RM 2.4-3.8) and Rkm 12.2-15.4 (RM 7.6-9.6) for monitoring incidence of GBT. Experiments to monitor early life history stages of trout were conducted at Rkm 2.4 (RM 1.5), Rkm 8.0 (RM 5.0) and Rkm 14.5 (RM 9.0).

WATER CHEMISTRY, TROUT POPULATIONS AND FIELD BIOASSAYS

Methods

Water Chemistry

Water samples for analysis of common ions and nutrients were collected monthly at the Saint Xavier gagehouse 0.2 km downstream of Afterbay Dam from 5 January - 1 December, 1987 and delivered to Northern Engineering and Testing, Inc. in Billings for processing. Nutrient samples were preserved with sulfuric acid.

Gas Saturation Measurements and Formulas

During 1987 gas saturation levels were recorded two to three times per week at the gagehouse, Rkm 4.8 (RM 3.0), and at each early life history study site (Figure 1). Parameters measured included delta P (the difference between total gas pressure in water and in air), absolute barometric pressure, water temperature and dissolved oxygen concentration. Delta P was determined using a Bouck gasometer (Bouck 1982), which was allowed 30 min to reach equilibrium before each measurement. Barometric pressure was measured at the site with a Thommen 22000 pocket altimeter-barometer and in the office two to three times daily using a Princo Nova, fortin type mercurial barometer. Water temperature was measured with a mercury thermometer and dissolved oxygen was determined using liquid reagents and the azide modification of the Winkler method (APHA 1976). Formulas used to calculate gas levels are discussed thoroughly by Colt (1984) and include:

% Total Saturation = [(BP + ^P) / BP] * 100

% O_2 Saturation = ([O_2]/B-O_2 * 0.5318) / ((BP - P-H_2O) * 0.20946)) * 100

% N_2 + Ar Saturation = [(BP + ^P - ([O_2]/B-O_2) * 0.5318) - P-H_2O) / (BP - P-H_2O) * 0.7902] * 100

^P = TGP - BP

^P-O_2 (mm Hg) = [O_2]/B-O_2 * 0.5318 - 0.20946*(BP - P-H_2O)

^P-N_2 + Ar (mm Hg) = BP + ^P - [O_2]/B-O_2 * 0.5318 - P-H_2O - 0.7905*(BP - P-H_2O)

TGP = BP + ^P

P-O_2 (mm Hg) = [O_2]/B-O_2 * 0.5318

P-N_2 + Ar (mm Hg) = BP + ^P - [O_2] - P-H_2O

$$\text{B-}O_2 = e^{[A1 + A2*(100/T) + A3*\log e\ (T/100)]}$$

$$\text{P-}H_2O = 760 \times e^{[24.4543 - 67.4509*(100/T) - 4.8489 * \log e\ (T/100)]}$$

Where: BP = Barometric pressure (mm Hg)
^P = Delta P (mm Hg)
[O_2] = Dissolved oxygen concentration (mg/l)
B-O_2 = Bunsen coefficient of oxygen (L/L x atm)
P-H_2O = Vapor pressure of water (mm Hg)
TGP = Total gas pressure (mm Hg)
^P-O_2 = Oxygen Component of ^P (mm Hg)
^P-N_2 + Ar = Nitrogen and Argon Component of ^P (mm Hg)
P-O_2 = Oxygen Pressure (mm Hg)
P-N_2 + Ar = Nitrogen and Argon Pressure (mm Hg)
T = Absolute water temperature (^{o}C + 273.15)
A1 = -58.3877
A2 = 85.8079
A3 = 23.8439

Oxygen-nitrogen ratios were calculated using the O_2 and N_2 + Ar components of delta P or gas tensions, not % saturation.

Continuous Monitoring Equipment

Continuous recording water quality monitoring equipment included two Common Sensing tensionometers (model TBO-F at Rkm 0.6 and TGO-F at Rkm 4.8) and two Hydrolab's system 8000. Equipment was first installed at the gagehouse and Rkm 4.8 (RM 3.0) during spring 1985. The tensionometers measure water temperature and total gas, oxygen, and nitrogen pressures. In addition to these parameters, model TBO-F also measures barometric pressure. The Hydrolab records water temperature, dissolved oxygen concentration, pH, conductivity and oxidation-reduction potential. The tensionometers and Hydrolab were interfaced with a Sutron satellite system which relays measurements taken every 30 min, 24 h per day to an earth station in Boise, Idaho and a computer in Billings, Montana. Equipment was calibrated using the manufacturer's recommended procedures. Accuracy was assessed by comparing meter readings with water temperatures from a mercury thermometer, dissolved oxygen concentrations determined from a Winkler and total gas pressures from one or two Bouck gasometers.

Temperatures were monitored at several points throughout the study area. A MDFWP Taylor 30-d thermograph was maintained at the Saint Xavier gagehouse below Afterbay Dam. Additional continuous recording temperature equipment was installed by the Bureau of Reclamation at the gagehouse and at Rkm 4.8 (RM 3.0). Maximum/minimum thermometers were located at Rkm 2.4, 8.0, 14.5, (RM 1.5, 5.0 and 9.0). Water temperature monitoring of the Bighorn Lake Forebay was initiated on 15 April, 1987 and data were collected via the Hydromet system.

GBT Incidence of Occurrence

Incidence of gas bubble trauma and progression and duration of symptoms were monitored using a boom-mounted electrofishing system equipped with either a 110 or 220 volt rectifying unit. Electrofishing runs were conducted at night if capture efficiencies were low during daylight hours or if recreational fishing pressure was high. Approximately 150 brown trout and as many rainbow trout as possible were examined biweekly or monthly for external symptoms of gas bubble trauma. Lengths, weights, sex, missing fins and the presence of hooking scars were recorded. A rating system was used to categorize fish into one of four groups:

Category

0 - No visible external symptoms.

1 - Minor symptoms: Symptoms normally restricted to a few bubbles on fins or a bubble in one eye. Fish in this category do not appear seriously stressed.

2 - Serious symptoms: Numerous bubbles present in fins; bubbles may also be found in the skin, inside the the mouth, on the opercle, or in one eye. Fish in this category appear stressed.

3 - Severe symptoms: Large numbers of gas bubbles are present; hemmorhaging and/or fungal growth may also occur and one or both eyes may be blind. These fish are severely debilitated, lethargic and have a poor condition factor. Chances for survival appear questionable.

A rating system was also developed to describe the severity of gas bubble trauma on each fin or body part. Parts exhibiting

GBT symptoms were assigned one of the following codes:

H - High numbers of bubbles present.
M - Moderate numbers of bubbles present.
L - Low numbers of bubbles present.
R - Recovering but scars from previous bubbles apparent.

A total GBT rating that numerically summarized the severity and proportion of GBT on affected external surfaces of individual fish was developed. Fins or body parts with high, moderate, low and no visible GBT symptoms present were assigned numerical values of 3, 2, 1, and 0, respectively. A total of 18 body parts were included in the total GBT rating, resulting in values ranging from 0 to a maximum of 54. Values approaching the maximum would be considered rare and a non-normal distribution would be expected.

Since the inception of the study, approximately 2004 trout in the upper 6.1 Rkm (3.8 miles) of the river have been marked with numbered Floy t-tags that were treated with algacide. Subsequent recaptures of these fish allowed us to evaluate the progression or remission of GBT symptoms.

Population Estimates

Boat-mounted, fixed electrode electofishing systems were used by MCFRU and MDFWP personel to conduct fish population estimates. Multiple mark and recapture trips were made to obtain adequate sample sizes; procedures were those of Vincent (1971 and 1974), adapted for computer analysis. Population estimates were made separately for various length interval groupings. At least four (but usually seven or more) recaptured trout were included within each 1.3 cm (0.5 inch) length interval. After reading scales, an estimate for each age was obtained by a summation of the proportions found in each size group. Population estimates were calculated using Chapman's modification of the Peterson formula (Ricker 1975) :

$$N = \frac{(M+1)\ (C+1)}{R+1}$$

where: N = Population estimate
M = Number of fish marked
C = Number of fish in the recapture sample
R = Number of marked fish in the recapture sample (C)

Embryo and Fry Survival

Brown and rainbow trout embryo survival from egg fertilization through hatching was tested using eggs and sperm obtained from Bighorn River spawning stock. Eggs from females and sperm from males were pooled to minimize handling or parental effects on egg survival. Eggs were incubated at various gas saturation levels including locations where saturation was high (Rkm 2.4; RM 1.5), medium (Rkm 8.0; RM 5.0), low (Rkm 14.5; RM 9.0), and in Afterbay Reservoir which served as a control (Figure 1).

On 20 November 1986, brown trout eggs were planted at each incubation site, including Afterbay Reservoir (control), in six egg incubation boxes (subsequently referred to as wedge boxes), containing 200 eggs each; also, a minimum of 1000 eggs were placed at each river site on Astroturf substrate in a modified Porter (1973) fry holding box. Eggs in the Astroturf were incubated to provide fry for rearing tests. The experimental design was repeated with rainbow eggs on 16 May 1987, except that only four wedge boxes were installed in Afterbay Reservoir, eight were placed at Rkm 2.4 and seven each at Rkm 8.0 and 14.5. Three of the wedge boxes planted on 16 May at Rkm 2.4 and two each at Rkm 8.0 and 14.5 were fitted with emergence tubes. Brown trout eggs were again planted on 19 November 1987 at each early life history study site. Six wedge boxes were placed at each river site and in Afterbay Reservoir and a modified fry holding box was installed at each of the three river sites.

All egg bags and emergence traps were completely enclosed and presifted 1.3-2.5 cm (0.5-1 inch) gravel was utilized. Wedge boxes simulated "natural" conditions and eliminated some ambient variables that could influence egg mortality. The wedge-shaped plywood box rested on top of the river bottom and effectively shed drifting aquatic vegetation; its rectangular main compartment measured 25.4 x 20.3 cm on each side. Five of the sides had 15.2 x 15.2 cm holes (covered with screen) to allow water movement through the gravel. The presifted 1.3-2.5 cm gravel in the egg compartment eliminated substrate as a variable and enclosing the eggs prevented mortality due to disturbance by spawning fish or fishermen. Fry loss due to lateral movement was also prevented. Two fiberglass egg bags containing 100 eggs each were placed in each wedge box. Eggs were enumerated using a paddle counter (Piper et al. 1982) which provided an exact count.

The emergence wedge boxes were equipped with 3.8 cm (1.5 in) PVC holding tubes containing fykes for collecting emerging swim-up fry at the downstream side of the trap.

Fry and fingerling were held at each early life history site in a 30.5 x 22.9 x 33 cm wooden box. Each box had three 24.1 x 12.7 cm and two 17.8 x 12.7 cm openings covered with 0.32 cm mesh screen. Fish were fed five or six times daily by a Sweeney model AF6 vibrator fish feeder equipped with an automatic timer powered by a 12 volt motorcycle battery. The feeder and holding box were enclosed in a larger wooden box attached to a steel post secured in the river bottom.

Statistics

Statistical tests were performed using methods described by Snedecor and Cochran (1967). Significant differences were, unless otherwise stated, those with $P < 0.05$.

Results and Discussion

Water Chemistry

In 1987, water samples were collected monthly from the Bighorn River at the gagehouse. Water discharged from Bighorn Lake was hard and had relativly high alkalinity, conductivity, and total dissolved solid levels (Table 1). As in 1985 and 1986, sodium and calcium were the cations found in the highest concentrations. Magnesium concentrations were about two-thirds lower on a milligrams/liter basis. However, when compared on a milliequivalent/liter basis, magnesium concentrations were 66 and

Table 1. Mean and ranges of water quality parameters of 12 samples from the Bighorn River at the gagehouse below Afterbay Dam from 5 January - 1 December, 1987.

Parameter	Mean	Range	meq/l
Total Hardness (mg/l as $CaCO_3$)	284	209-332	5.68
Total Alkalinity (mg/l as $CaCO_3$)	153	80-172	3.06
Bicarbonate Alkalinity (mg/l HCO_3)	186	98-210	3.05
Calcium (mg/l)	73	49-85	3.65
Magnesium (mg/l)	25	20-29	2.08
Sodium (mg/l)	73	59-92	3.17
Potassium (mg/l)	4	2-4	0.10
Chloride (mg/l)	10	7-13	0.29
Fluoride (mg/l)	0.4	0.3-0.6	0.02
Nitrate + Nitrite (mg/l)	0.53	0.36-0.96	0.04
Sulfate (mg/l)	264	188-332	5.50
Total Dissolved Solids (mg/l)	549	452-700	
Conductivity (micromhos/cm)	737	590-937	
pH	8.1	7.9-8.3	
Total Phosphorus as P (mg/l)	0.08[a]	<0.02-0.28	
Ortho-Phosphate as P (mg/l)	0.05[a]	<0.02-0.18	
Ammonia Nitrogen as N (mg/l)	0.20[a]	0.13-0.22[b]	
Total Kjeldahl Nitrogen as N (mg/l)	0.50[a]	<0.20-1.52[b]	

a - values below detection limits considered to be at detection limits.
b - change in detection limits

57% of calcium and sodium, respectively. Potassium levels continued to be low and were usually close to detection limits. As in previous years, the principle anions were sulfate and bicarbonate. Chloride is the only other anion present at any significant level. As found in 1985 and 1986, sulfate was present at higher concentrations than any other anion or cation and was higher than the 250 mg/l recommended for total dissolved solids in domestic water supplies (EPA 1976). The mean sulfate level was equal to that found in 1986, but it was 31 mg/l lower than 1985 levels. Anion and cation levels during 1987 were approximately the same as found in 1968 and 1969 by Wright and Soltero (1973). The mean lab pH was alkaline, 0.1 unit higher than in 1986, and varied only 0.4 units.

Mean total phosphorus and kjeldahl nitrogen concentrations were 0.08 and 0.50 mg/l, respectively. The mean total phosphorus level was equal to that found last year and, as in 1986, exceeded Montana water quality criteria for aquatic life on three sampling dates (DHES 1986). These elevated levels were 0.18 mg/l in June, 0.28 mg/l in October, and 0.11 mg/l in December. Wright and Soltero (1973) found higher total phosphorus levels in 1968-1969. Heavy growths of rooted macrophytes and cladaphora in the Bighorn River are probably related to these high nutrient levels. Ortho-phosphate averaged 0.05 mg/l and was below detection limits (0.02 mg/l) only during July sampling. Ortho-phosphate levels tended to mirror flucuations in total phosphorus and in July, August, and September samples, equaled total phosphorus. The mean ammonia concentration, which was 0.20 mg/l, was usually below detection limits and un-ionized ammonia was always less than 0.02 mg/l. However, if periods of high water temperature coincide with elevated pH levels, un-ionized ammonia concentrations may approach this level. Concentrations of ortho-phosphate and ammonia were similar to those found during 1985 and 1986 in this study and while ammonia was similar, ortho-phosphate was slightly lower in 1968 and 1969 (Wright and Soltero 1973). The 1987 mean total kjeldahl nitrogen was slightly higher than in 1986 and higher than the total organic nitrogen measured in 1968 and 1969 (Wright and Soltero 1973), but lower than that found in 1985. The maximum level (1.52 mg/l) occurred in October and coincided with high levels of total dissolved solids, total phosphorus, and ortho-phosphate.

The mean daily conductivity measured at the gagehouse by the Hydrolab 8000 was 858 micromhos/cm, or 121 micromhos/cm greater than the mean value determined from monthly samples. At the beginning of the year, conductivity was quite variable but tended to range between 765 and 810 micromhos/cm (Figure 2). It continued to increase throughout the spring until peaking on 25 April (931 micromhos/cm), and then declined through the summer. Two substantial but short term drops occurred in June and July. Specific conductance quickly rose from a low of 784 micromhos/cm on 14 September to another peak at 931 micromhos/cm in early October. Conductivity remained at this high level throughout the rest of 1987. The same pattern we observed in 1986 was displayed between May and December, except that conductivity increased to a higher level during fall 1987. This general pattern was also observed by Wright and Soltero (1973) in 1968 and 1969, although the magnitude of change appeared fairly low in 1969.

The pH of the Bighorn River at the gagehouse (Rkm 0.6) remained alkaline during January and February, varying from 8.6 to nearly 8.9 (Figure 3). Data collected from 9-27 February were erroneous; when problems were corrected the mean daily pH had dropped substantially and varied from approximately 8.1-8.4. A dramatic drop on 15 May may be a data collection error, but the current unavailability of short term data files for this time period prevented confirmation of this. In early June, pH increased from the 8.1-8.2 level to a peak of more than 8.8 on 9 June. A portion of the increase seen at the beginning of July was due to recalibration. A gradual decrease in pH occurred over

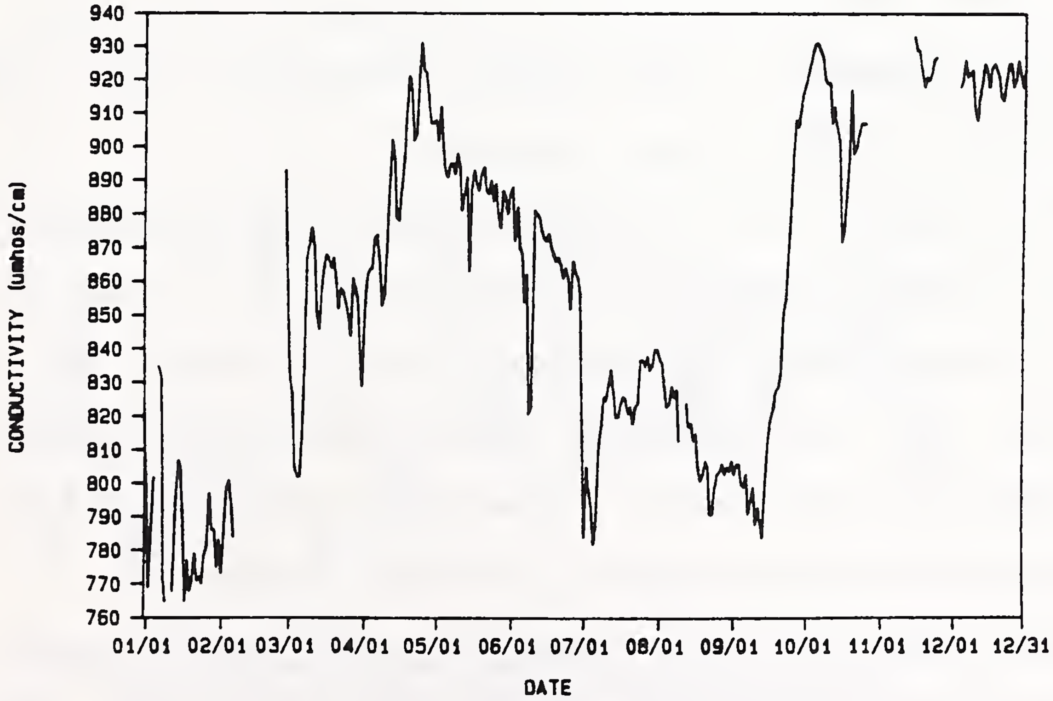


Figure 2. Mean daily specific conductance (micromhos/cm) of the Bighorn River at the gagehouse below Afterbay Dam during 1987.

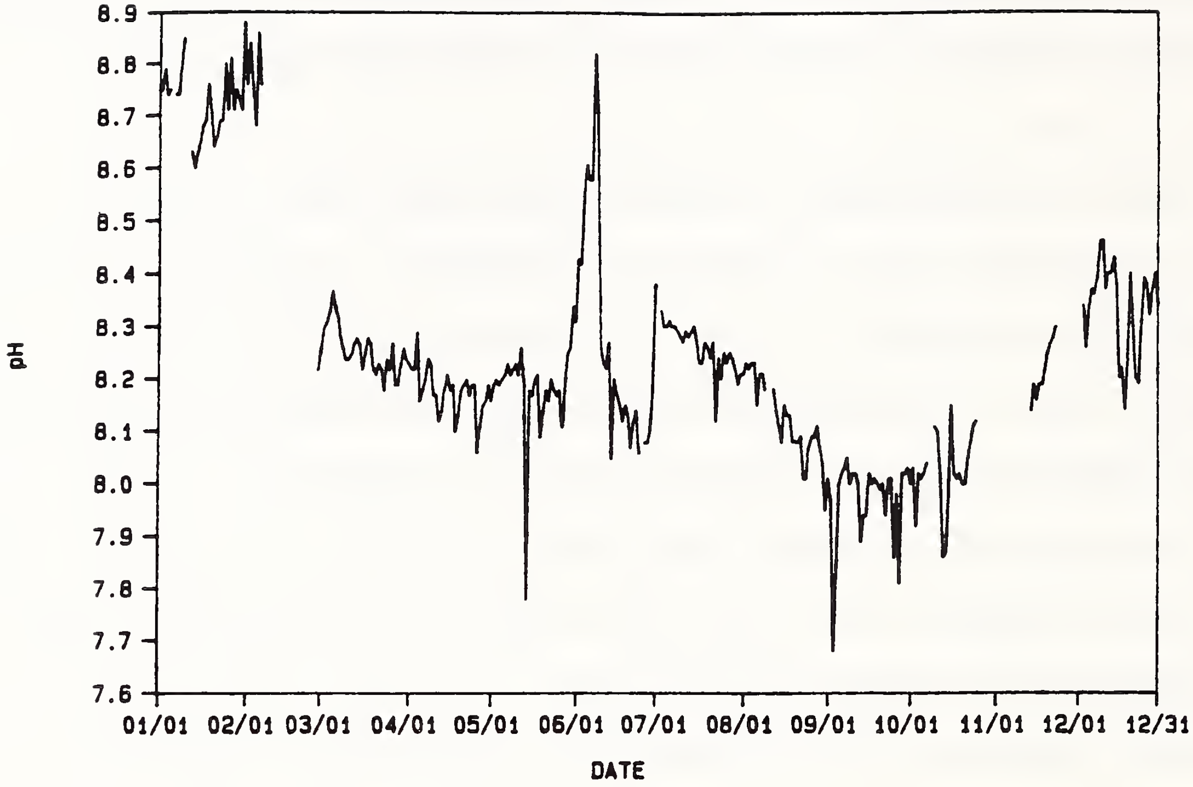


Figure 3. Mean daily pH of the Bighorn River at the gagehouse below Afterbay Dam from 1 January - 31 December, 1987.

the rest of the summer with the 1987 minimum of 7.68 being recorded on 4 September. From October through the rest of the year, a gradual rise in pH was observed.

As mentioned in the 1986 annual report, photosynthesis and respiration probably contribute substantially to diurnal and seasonal pH flucuations in the Bighorn River. During the first 10 d of June, 1987, regular daily fluctuations below Afterbay Dam were as large as 0.9 pH units, the mean pH was 8.53 (±0.28); over the entire period values ranged 1.32 units (Figure 4). Photosynthesis by algae and macrophytes would tend to reduce dissolved or free carbon dioxide levels during the day. This would trigger the carbonate-bicarbonate reaction to maintain equilibrium carbon dioxide, which would decrease hydrogen ion concentrations and increase pH. During periods of low light levels, as found during some afternoon thunderstorms and at night, respiration would continue to produce free carbon dioxide and the low photosynthetic activity would allow bicarbonate and hydrogen ion levels to increase and drop the pH. Greater photosynthetic activity further downstream may produce even more significant diurnal flucuations than those seen at the gagehouse.

Data from 11-20 December, 1987 provides a distinct contrast to the June data (Figure 5). Although the mean value for the 10 d period was lower by 0.2 units (8.33 ±0.13), the most important difference is the relative constancy over a 24 h period. Over this entire period the pH ranged 0.73 units, 0.59 units less than in June.

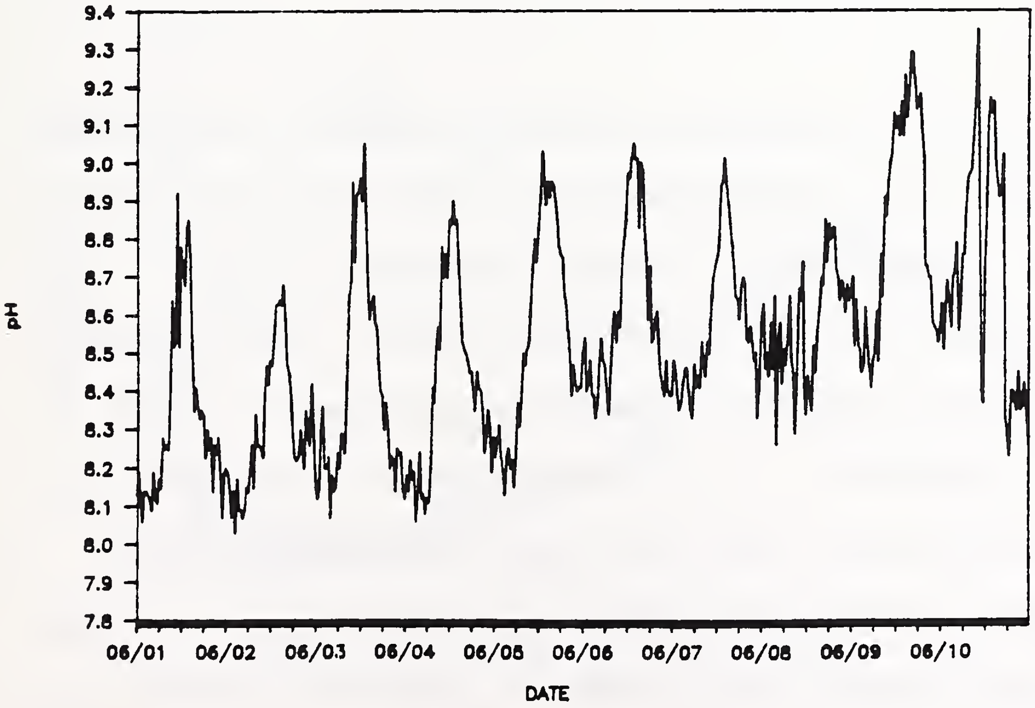


Figure 4. Diurnal pH levels of the Bighorn River (Rkm 0.6) during 1-10 June, 1987.

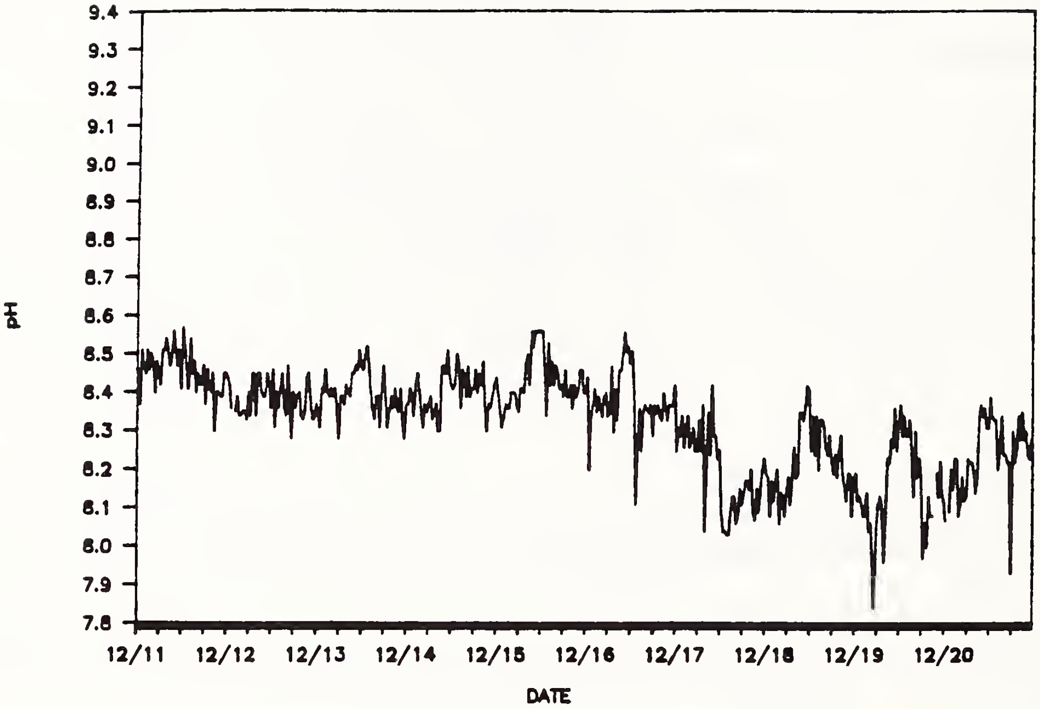


Figure 5. Diurnal pH levels of the Bighorn River (Rkm 0.6) during 11-20 December, 1987.

Water Temperature

As in 1986, water temperature patterns remained relatively constant through-out the study area during 1987 (Figures 6 and 7). Actual water temperatures, however, appeared to be intermediate of those measured in 1985 and 1986. Mean weekly water temperatures also showed a greater range than in 1986; they varied 0.9 C and were 7.7, 7.8, 8.4, and 8.6 C at Rkm 0.6, 2.4, 8.0, and 14.5 (RM 0.4, 1.5, 5.0, and 9.0), respectively. Minimum temperatures at all four sites occurred during the last week of February and ranged from 2.1-2.7 C (36-37 F) at Rkm 2.4 and 8.0, respectively. From April-September, temperatures increased in a downstream direction. During the rest of fall 1987, temperatures at the lower two sites were slightly lower than on the upper reaches of the river. Peak maximum temperatures were lower and occurred later than in 1986. Maximums were reached in mid-late September and varied from 15.1-16.3 C (59-61 F) at Rkm 2.4 and 8.0, respectively.

Additional water temperature data were continuously collected every 0.5 h at Rkm 0.6 (gagehouse) and Rkm 4.8 (RM 3.0) by Common Sensing tensionometers and from the epilimnion of Bighorn Lake at 15 min intervals by a Sutron-YSI thermistor (Figure 8). Water temperature at the gagehouse, as determined by the tensionometer, followed the same pattern as shown by the thermograph in Figure 6, but tended to be slightly warmer. The mean weekly water temperature measured by the tensionometer from mid-February - December, 1987 was 8.5 C (47 F), while thermograph readings

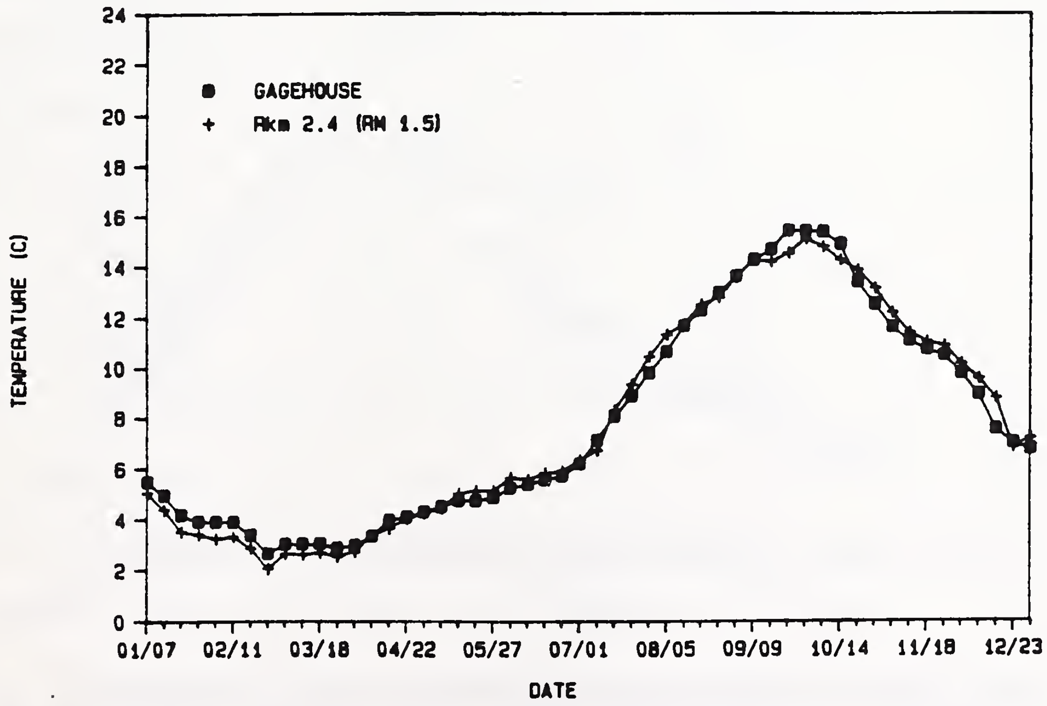


Figure 6. Mean weekly water temperatures of the Bighorn River at the gagehouse and Rkm 2.4 during 1987.

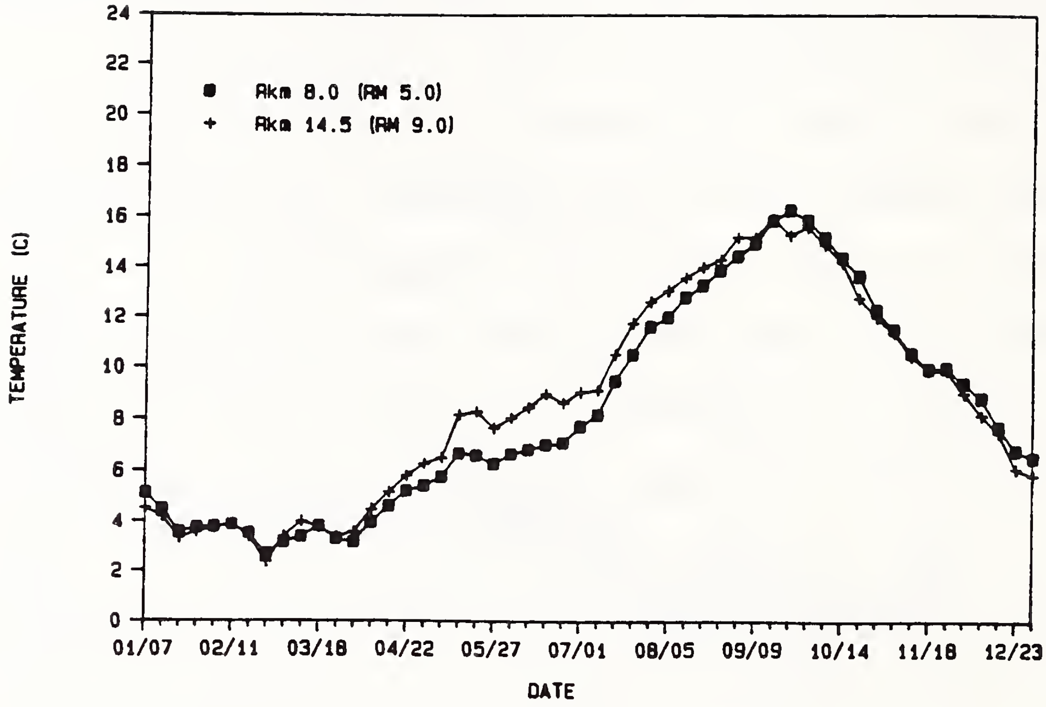


Figure 7. Mean weekly water temperatures of the Bighorn River at Rkm 8.0 and Rkm 14.5 during 1987.

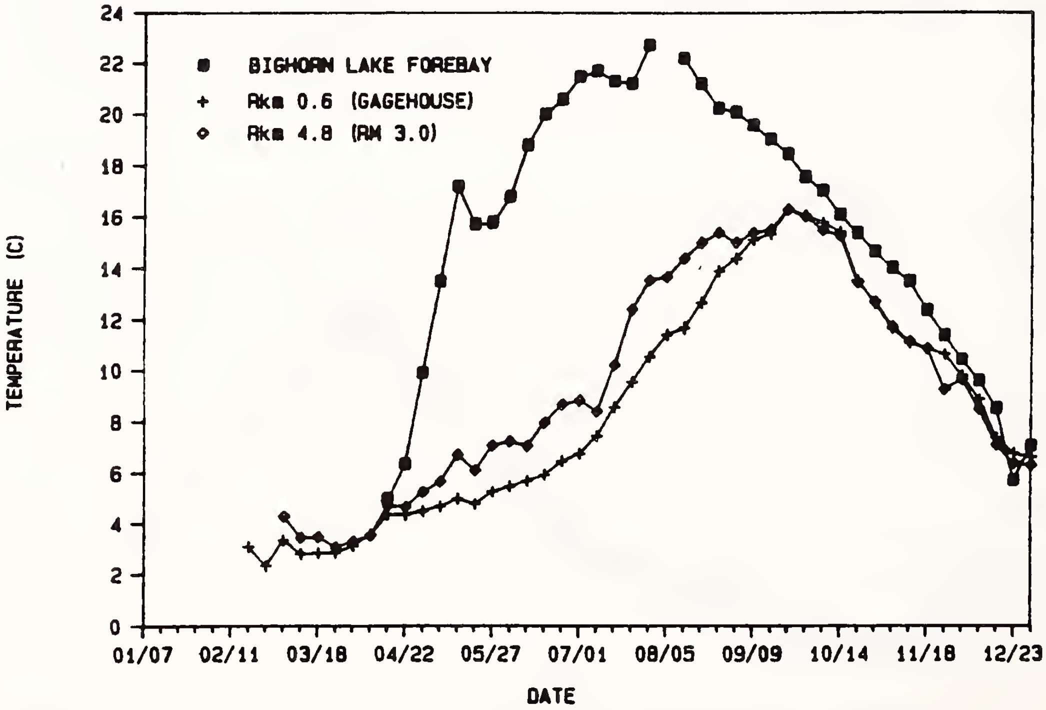


Figure 8. Mean weekly water temperatures of the forebay epilimnion of Bighorn Lake, the Bighorn River at the gagehouse (Rkm 0.6), and Rkm 4.8 in 1987 reported via the Hydromet system.

produced a mean weekly value 0.2 C lower. Water temperature at Rkm 4.8 remained higher than the two upstream sites through mid-October. It also tended to be warmer than the downstream locations from late July - October. All river sites displayed a very different thermal regime than the forebay epilimnion of Bighorn Lake (Figure 8) and showed the impact of the deep-water release from Yellowtail Dam. Water temperature in the forebay was substantially warmer than the Bighorn River through the summer and fall. The maximum weekly mean temperature was 22.7 C (73 F), but may have been higher during August when the thermistor was inoperative.

Discharge

Mean daily discharge from Afterbay Dam in 1987 contrasts sharply with the 1986 hydrograph. Unlike 1986, no high water period was recorded (Figure 9). From 1 January - 26 March, flows remained near 3000 cfs (84.96 m^3/s), except for an increase to 3283 cfs (92.97 m^3/s) for 6 d from 9-14 January and a drop to 2900 cfs (82.13 m^3/s) for about 3 d in early March. In late March flows were increased to peak levels near 4000 cfs (113.28 m^3/s); the maximum mean daily discharge was 4027 cfs (114.04 m^3/s) and occurred on 2 April. This flow was maintained for 2 weeks, afterwhich discharge was gradually decreased from 3000 cfs to between 2200 and 2600 cfs (62.30-73.63 m^3/s). Flows were again decreased in mid-July and were maintained between 2200 and 1750 cfs (62.30-49.56 m^3/s) until late October. This is a dramatically different flow regime than in 1986, when discharge peaked in June at 7431 cfs (210.45 m^3/s) and remained over 5000 cfs (141.60 m^3/s) until early August. The discharge measurement of springs below Yellowtail Dam on 20 October resulted in the mean daily flow decreasing to 1218 cfs (34.49 m^3/s). During the rest of 1987, flows ranged from 2500-3050 cfs (70.80-86.38 m^3/s). The mean daily discharge from Afterbay Dam in 1987 was 2612 cfs (73.97 m^3/s).

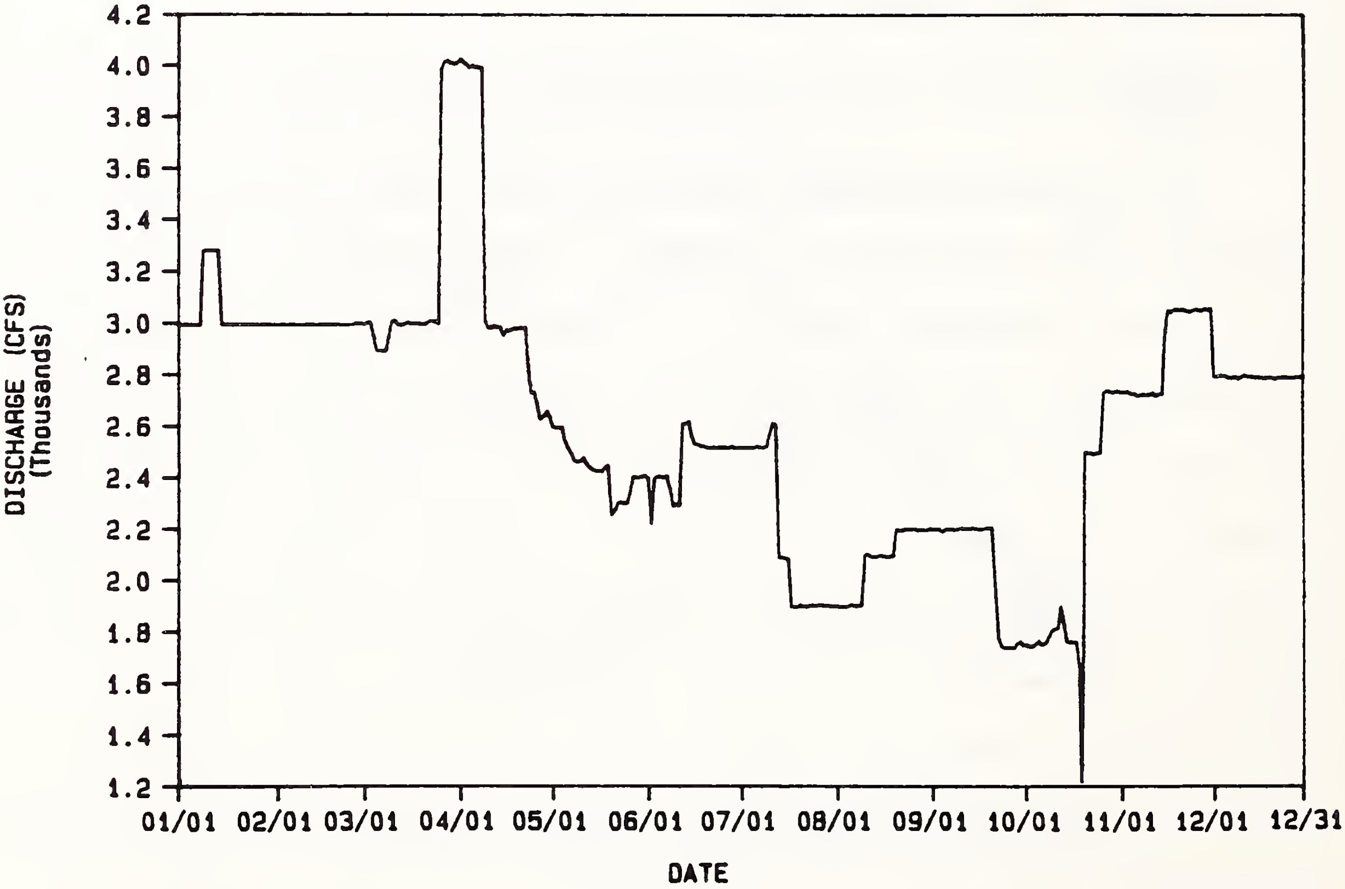


Figure 9. Mean daily discharge of the Bighorn River below Afterbay Dam during 1987.

Gas Monitoring

The mean annual values of oxygen, nitrogen and argon, barometric pressure, and temperature measured at five sites on the Bighorn River during 1987 displayed the same general pattern as seen in 1985 and 1986 (Tables 2 and 3). In contrast, the mean TGP remained more constant throughout the study area than in previous years; in 1986 the mean annual TGP decreased 4.8% between the gagehouse and Rkm 14.5 but decreased only 1.7% in 1987. Except at the gagehouse (Rkm 0.6), mean annual TGP was higher at each site in 1987 than in 1986 or 1985. Also, all stations had maximum TGP measurements greater than in 1986; the highest maximum was 128.0% at Rkm 14.5. Mean annual nitrogen

Table 2. Means and range of water temperature and dissolved gas levels at five sites on the Bighorn River below Afterbay Dam, 1 January - 31 December, 1987.

River km	Sample size	Temp. (C)	D.O. (mg/l)	% saturation Oxygen	% saturation N_2+Ar	% saturation Total
0.6	135	7.6	11.7	108.3	118.7	116.3
		(2.2-15.6)	(8.5-13.5)	(96.9-118.8)	(110.2-124.9)	(109.2-122.7)
2.4	127	7.9	12.4	116.4	116.2	116.0
		(2.5-15.8)	(9.4-14.6)	(101.6-135.5)	(108.8-122.3)	(108.5-122.7)
4.8	119	9.6	14.0	137.3	110.3	115.7
		(2.8-17.2)	(9.8-18.7)	(102.7-197.1)	(100.4-121.3)	(106.8-127.9)
8.0	133	8.9	13.9	134.9	110.4	115.1
		(2.8-16.9)	(9.7-18.0)	(102.3-187.1)	(102.7-117.3)	(106.3-126.0)
14.5	122	10.1	14.7	146.2	106.6	114.6
		(2.8-18.1)	(9.6-20.2)	(100.7-220.1)	(98.6-115.2)	(102.9-128.0)

Table 3. Means and ranges of barometric, delta P, oxygen, and calculated nitrogen pressures (mm Hg) at five sites on the Bighorn River below Afterbay Dam, 1 January - 31 December, 1987.

River km	B.P. (mm Hg)	^P (mm Hg)	^P-O_2 (mm Hg)	^P-N_2+Ar (mm Hg)	O_2 (mm Hg)	N_2+Ar (mm Hg)
0.6	680 (667-691)	111 (63-153)	12 (-4-26)	99 (58-132)	152 (134-167)	630 (590-664)
2.4	680 (666-691)	109 (58-154)	23 (2-50)	86 (46-117)	164 (143-191)	617 (576-652)
4.8	680 (665-691)	107 (46-188)	52 (4-137)	55 (2-113)	193 (145-277)	584 (522-647)
8.0	680 (665-691)	102 (43-177)	48 (3-123)	55 (14-91)	188 (144-264)	585 (540-620)
14.5	680 (666-691)	100 (20-191)	65 (1-168)	35 (-8-81)	205 (142-312)	565 (521-616)

levels remained slightly above 110% saturation at Rkm 4.8 and 8.0 and dropped down to 106.6% at Rkm 14.5. These values are 1.1-2.6% lower than levels found in 1986. Since TGP was higher at most sites and nitrogen and argon saturation was lower than in previous years, it would appear likely that oxygen became a larger component of TGP. Oxygen saturation increased 1.4-17.0% over 1987 mean values with the larger increases occurring in the lower reaches of the study area. The increased importance of oxygen as a component of TGP may have implications when related to GBT in trout.

Mean barometric pressure was 680 mm Hg at all sites and ranges were essentially identical. Higher minimums and lower maximums contributed to the smaller range of barometric pressure during 1987 when compared to 1986. Mean barometric pressures were lower during the last quarter than during the first three quarters of 1987 (Appendix Tables 2, 4, 6, and 8).

Mean water temperatures determined from instantaneous measurements with a laboratory-grade mercury thermometer showed a variation of 2.5 C. The greater variation over max/min thermometers and thermographs was probably due to the single daily measurements and obtaining the downstream temperatures later in the day.

Although levels were more constant than in the past, mean annual total saturation and delta P decreased most, both numerically and on a per kilometer basis, between Rkm 4.8 and 8.0. The second largest drop on a longitudinal linear basis was between Rkm 0.6 and 2.4. As last year, dissipation of nitrogen and argon gas increased to a maximum rate level between Rkm 2.4 and 4.8. It decreased to zero between Rkm 4.8 and 8.0, then increased again but not to the previous rate level. In contrast to nitrogen and argon, oxygen levels rose the most between Rkm 2.4 and 4.8. The rate of increase of oxygen was highest in the upper reaches of the river (Rkm 0.6-4.8).

Mean TGP's at all five river sites were highest during the second quarter of 1987. The lowest quarterly means at Rkm 0.6, 2.4, and 4.8 were found in the first and in the fourth quarters at Rkm 8.0 and 14.5 (Appendix Tables 1-8).

As in 1986, hyperbaric pressures remained more consistent and nitrogen pressures were higher at Rkm 0.6 than at the downstream sites (Figures 10-19). The range of delta P increased

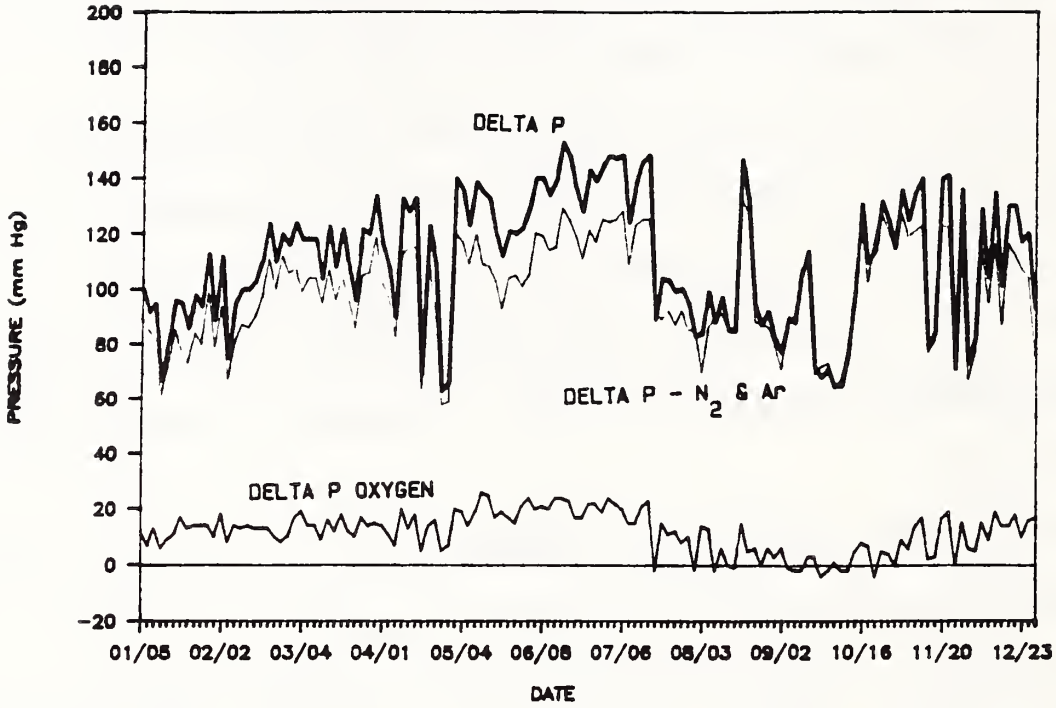


Figure 10. Delta P, P-O_2, and P-N_2+Ar (mm Hg) measured at Rkm 0.6 (gagehouse) on the Bighorn River during 1987.

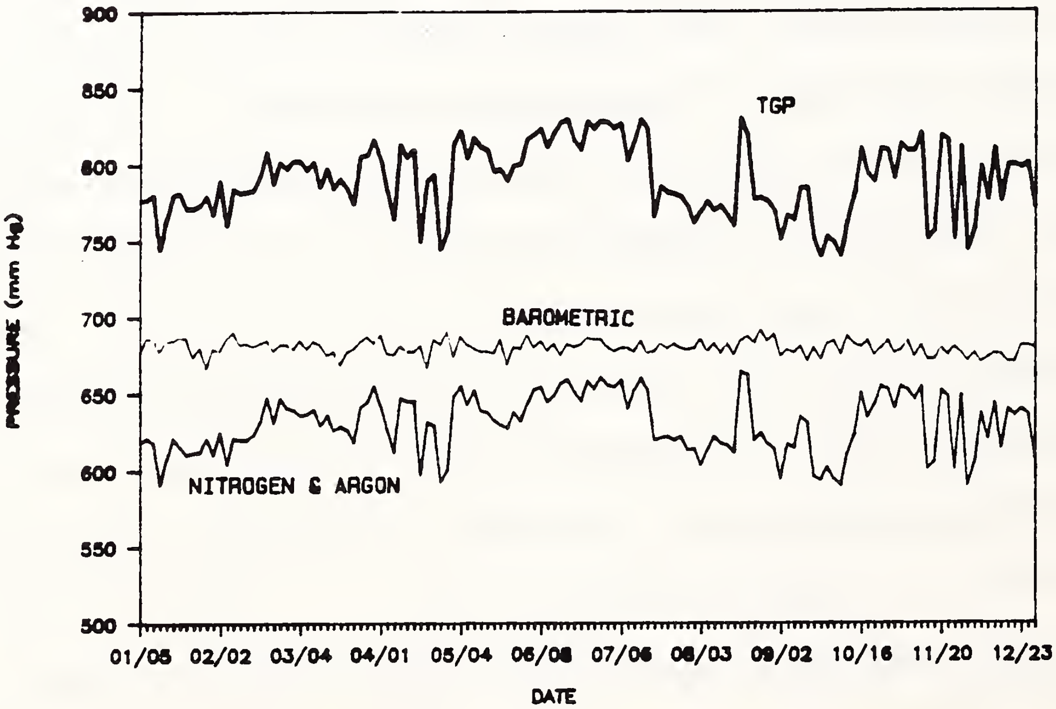


Figure 11. Total (TGP), nitrogen and argon tensions, and barometric pressure (mm Hg) measured at Rkm 0.6 (gagehouse) on the Bighorn River during 1987.

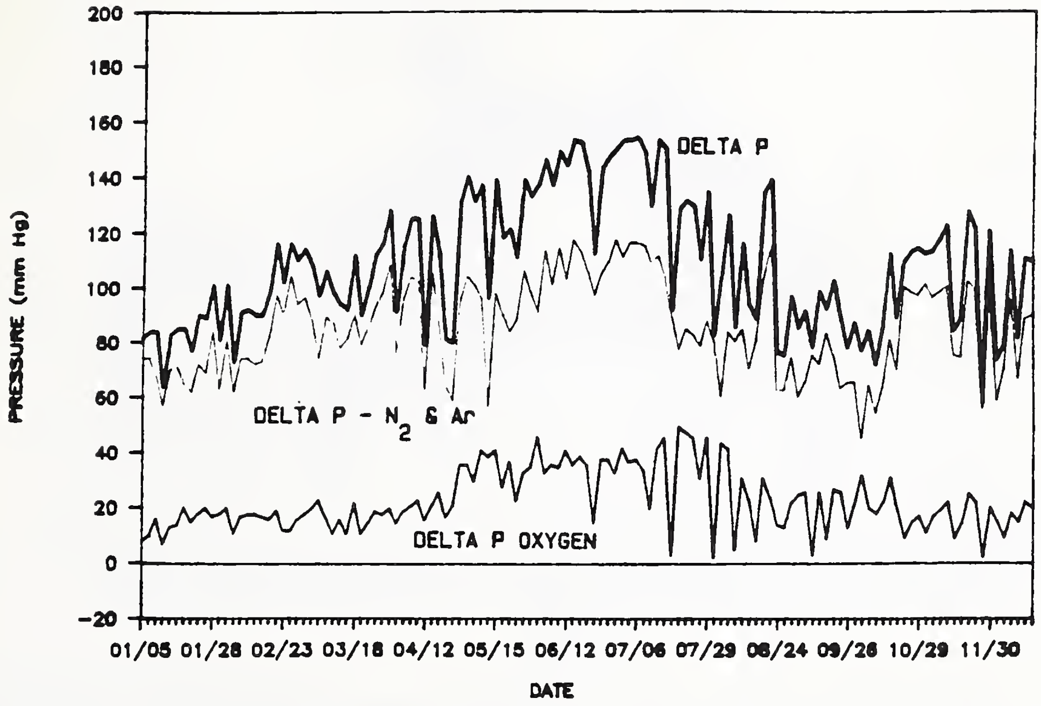


Figure 12. Delta P, P-O_2, and P-N_2+Ar (mm Hg) measured at Rkm 2.4 (RM 1.5) on the Bighorn River during 1987.

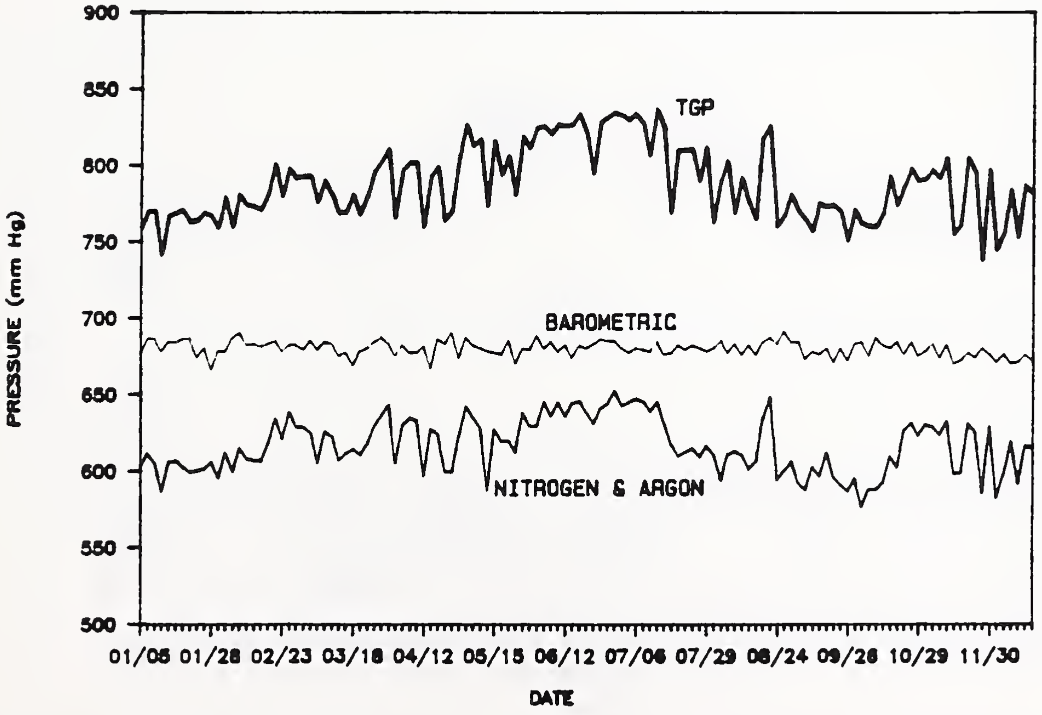


Figure 13. Total (TGP), nitrogen and argon tensions, and barometric pressure (mm Hg) measured at Rkm 2.4 (RM 1.5) on the Bighorn River during 1987.

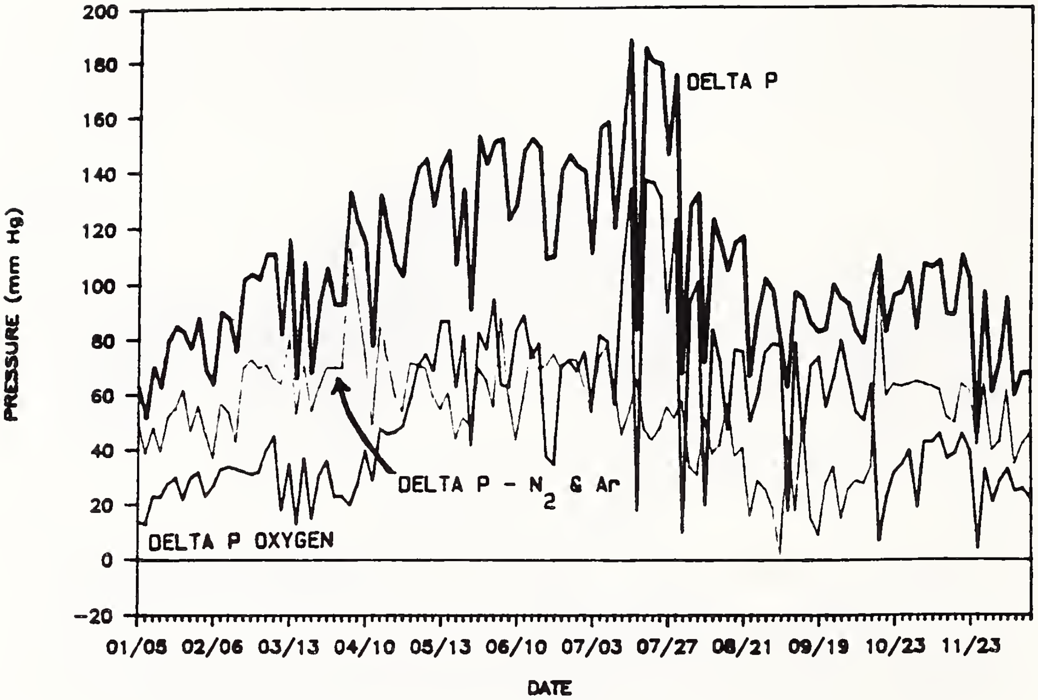


Figure 14. Delta P, P-O_2, and P-N_2+Ar (mm Hg) measured at Rkm 4.8 (RM 3.0) on the Bighorn River during 1987.

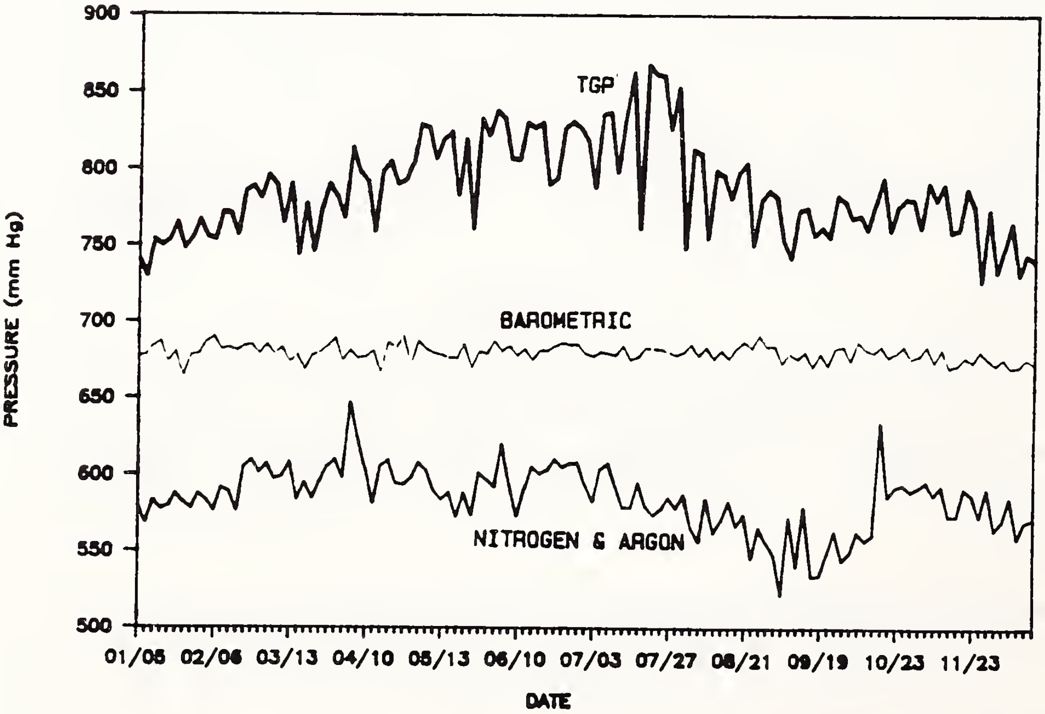


Figure 15. Total (TGP), nitrogen and argon tensions, and barometric pressure (mm Hg) measured at Rkm 4.8 (RM 3.0) on the Bighorn River during 1987.

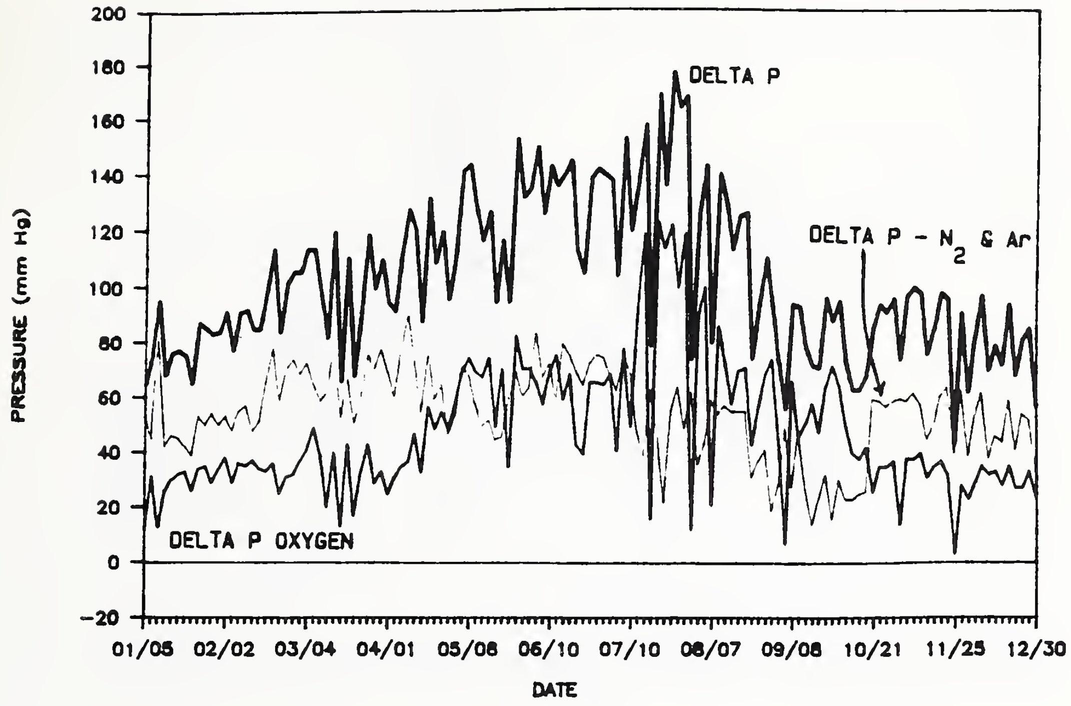


Figure 16. Delta P, P-O_2, and P-N_2+Ar (mm Hg) measured at Rkm 8.0 (RM 5.0) on the Bighorn River during 1987.

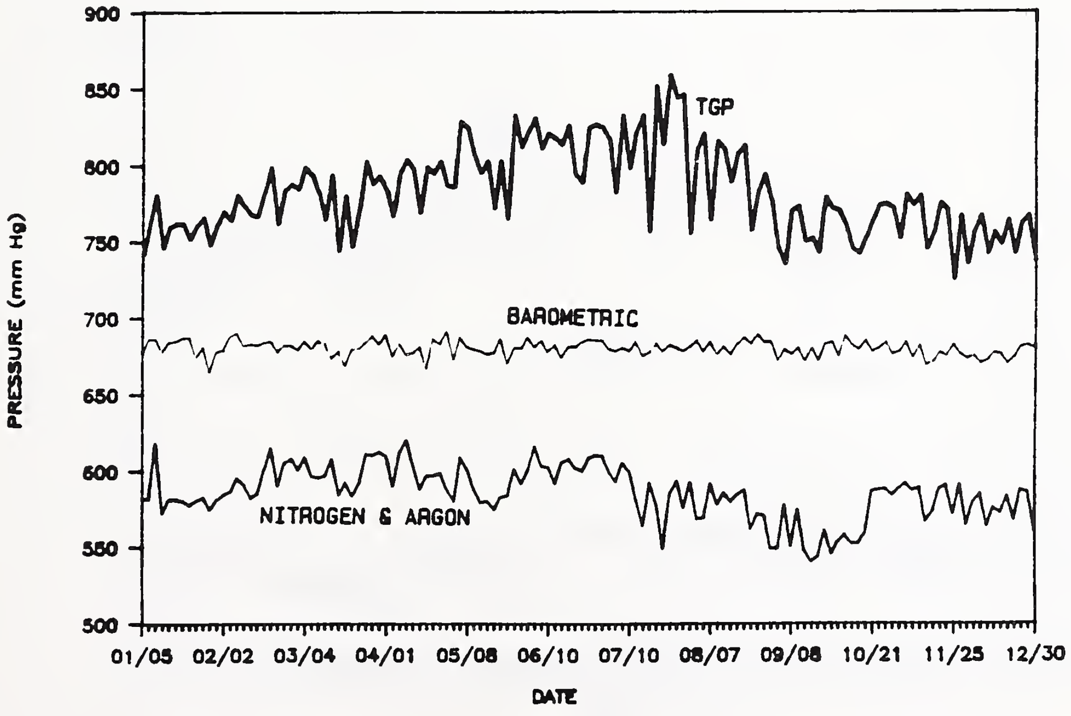


Figure 17. Total (TGP), nitrogen and argon tensions, and barometric pressure (mm Hg) measured at Rkm 8.0 (RM 5.0) on the Bighorn River during 1987.

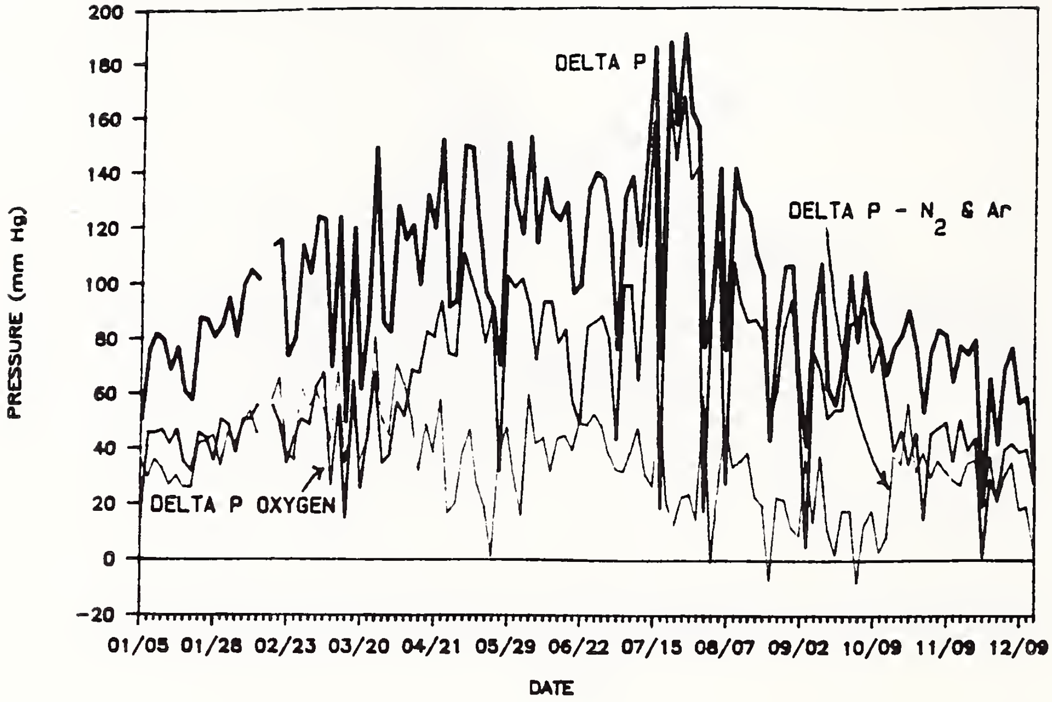


Figure 18. Delta P, P-O_2, and P-N_2+Ar (mm Hg) measured at Rkm 14.5 (RM 9.0) on the Bighorn River during 1987.

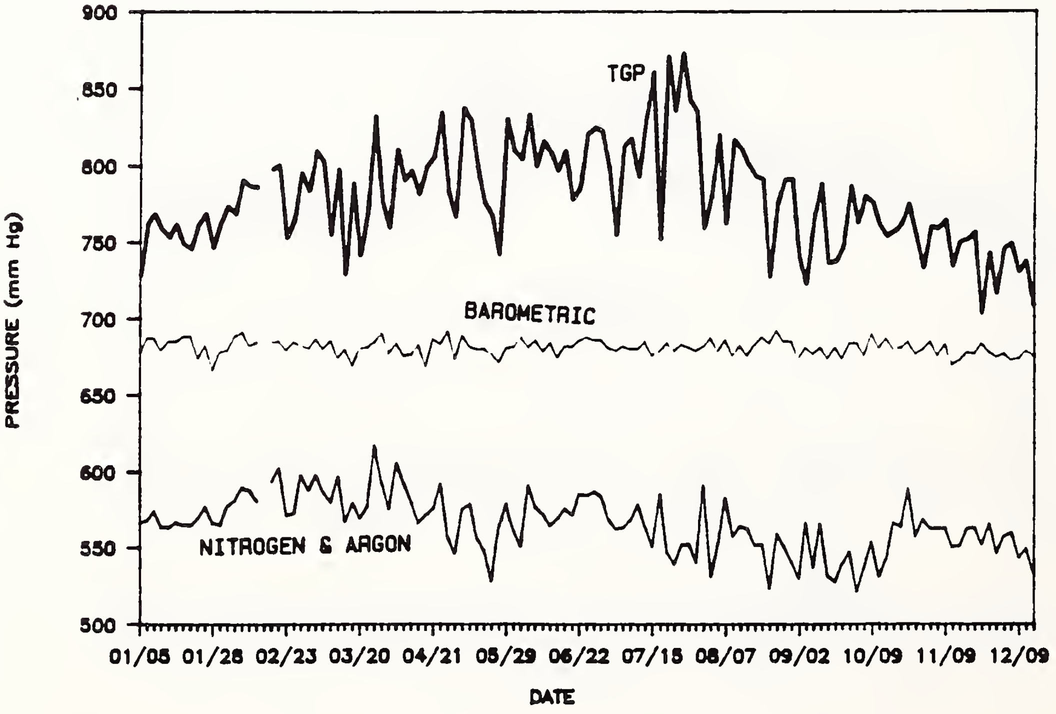


Figure 19. Total (TGP), nitrogen and argon tensions, and barometric pressure (mm Hg) measured at Rkm 14.5 (RM 9.0) on the Bighorn River during 1987.

at each downstream site, except between Rkm 4.8 and 8.0. The variability of delta P increased from 90 mm Hg at Rkm 0.6 to 171 mm Hg at Rkm 14.5 (Table 3). As with temperature and most gas levels, a larger range was found at Rkm 4.8 than at Rkm 8.0. This increased variation may be due in large part to changes in solar insolation and the increasing importance of oxygen. However, other factors such as changes in the aeration rate on various reaches of the river, gas entrainment, river discharge, and water temperature can also affect the variation. At Rkm 2.4, nitrogen and argon continued to be the primary component of the hyperbaric pressure during the entire year (Figure 12). Further downstream however, nitrogen and argon gas become a less important portion of both TGP and delta P, particularly from late spring - early fall (Figures 14-19).

In general, total delta P's at all sites increased from January to mid-June and July. The maximum delta P at Rkm 0.6 was 153 mm Hg on 15 June. All other maximum delta P's were measured in July; maximum hyperbaric pressures were 154, 188, 177, and 191 mm Hg at Rkm 2.4, 4.8, 8.0, and 14.5, respectively. So, although mean TGP and nitrogen and argon tensions tend to be lowest at Rkm 14.5, the highest TGP measurements were recorded at this site. Delta P's at all sites except Rkm 0.6 showed a gradual decrease throughout the rest of 1987. A rather abrupt change occurred at Rkm 0.6, where delta P decreased nearly 60 mm Hg between measurements on 15 and 17 July. Gas pressures remained low at Rkm 0.6 from mid-July to mid-October except for two high measurements in late August and a smaller decrease in mid-September. Decreases in delta P at the gagehouse usually coincided with sluiceway gate openings of 1.0 ft or less. Decreased delta P also occurred when one sluice gate malfunctioned and was stuck open at 1.53 ft. Minimum delta P's at all sites except Rkm 0.6 were measured on 25 November; the minimum delta P at Rkm 0.6 was obtained in late April.

In 1986, highest gas levels coincided with peak discharge (6000 - 7431 cfs; 169.9 - 210.5 m^3/s). Maximum gas levels in 1987, however, did not correlate well with flow. Peak flows (4027 cfs; 113.28m^3/s) occurred in early April 1987, while maximum gas levels peaked between 15 June - 31 July, 1987, when mean discharge was 2305 cfs (65.28 m^3/s) and ranged from 1896-2619 cfs (53.69-74.17 m^3/s). The mean discharge during July, when maximum delta P's were observed at all the stations downstream from the gagehouse, was even lower at 2190 cfs (62.02 m^3/s). This suggests that factors other than total discharge control the production of gas supersaturation below Afterbay Dam.

As might be expected from delta P and TGP data, oxygen pressure determined by modified Winkler samples tended to increase and become more volatile in a downstream direction (Figures 20-24). Oxygen peaked in late spring at Rkm 0.6 and in late July at all other sites. The highest oxygen levels, 220.1% saturation and 312 mm Hg, were measured at Rkm 14.5.

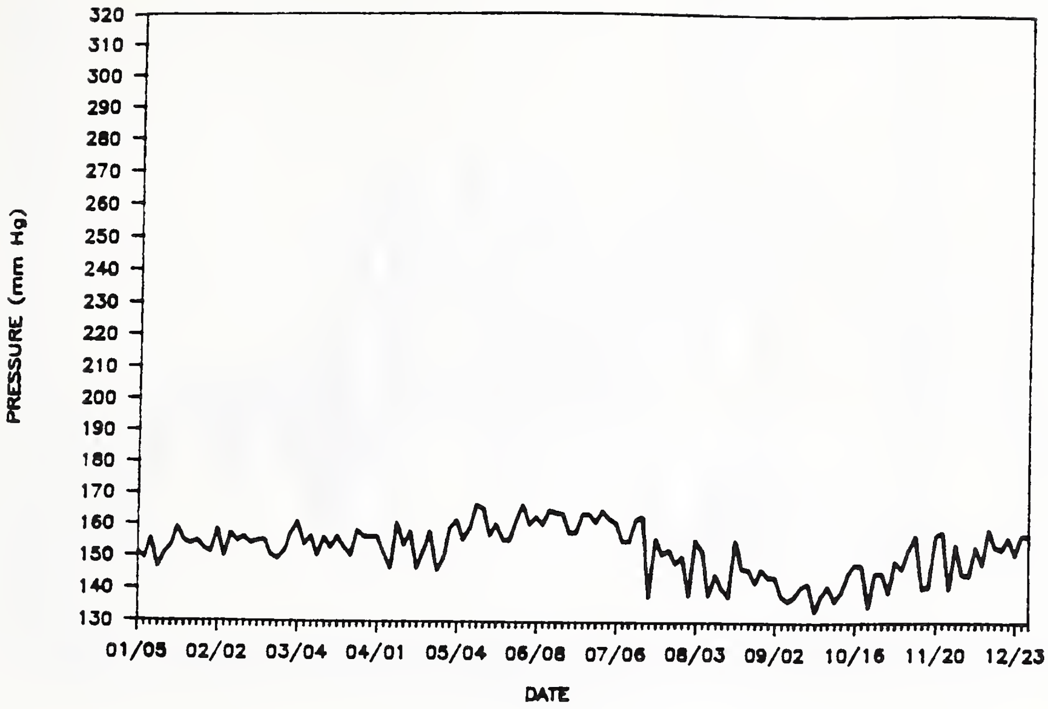


Figure 20. Oxygen pressure (mm Hg) determined from modified Winkler samples collected at Rkm 0.6 (gagehouse) on the Bighorn River during 1987.

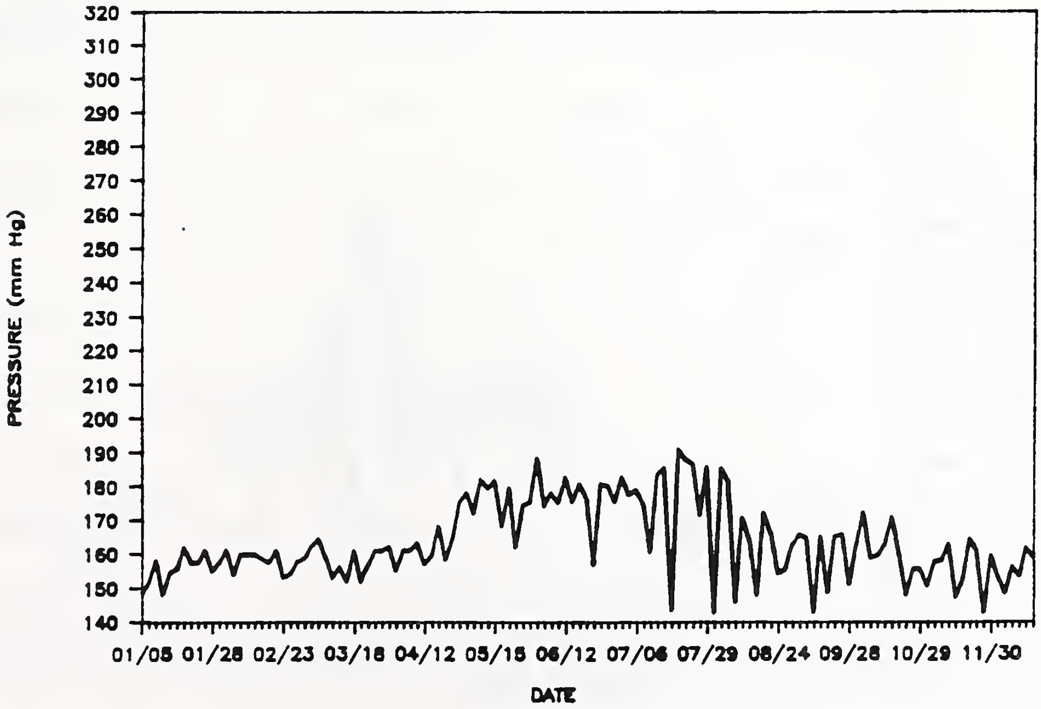


Figure 21. Oxygen pressure (mm Hg) determined from modified Winkler samples collected at Rkm 2.4 (RM 1.5) on the Bighorn River during 1987.

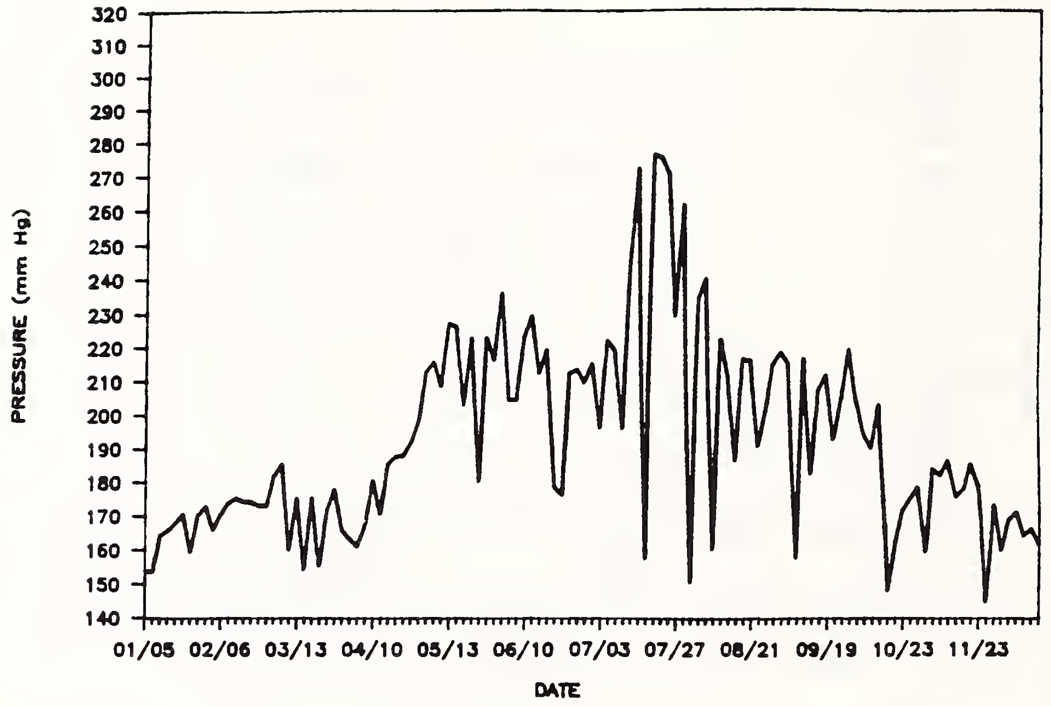


Figure 22. Oxygen pressure (mm Hg) determined from modified Winkler samples collected at Rkm 4.8 (RM 3.0) on the Bighorn River during 1987.

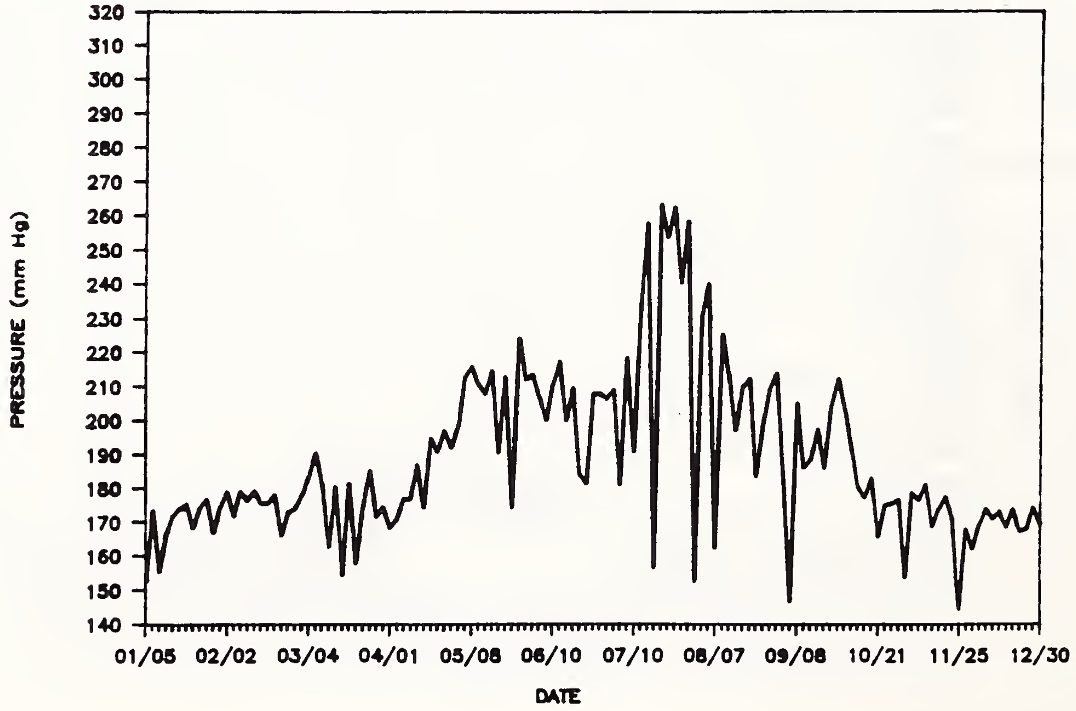


Figure 23. Oxygen pressure (mm Hg) determined from modified Winkler samples collected at Rkm 8.0 (RM 5.0) on the Bighorn River during 1987.

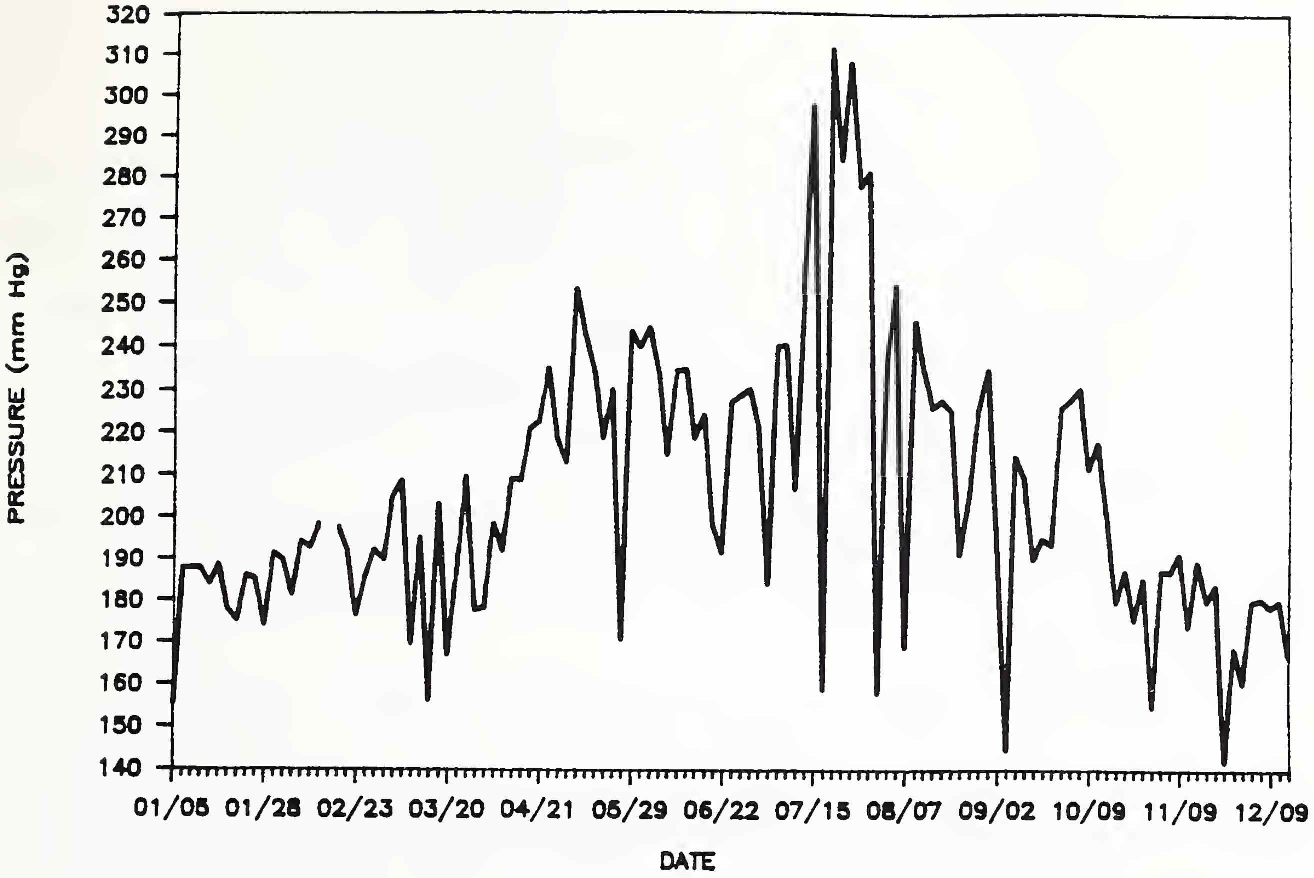


Figure 24. Oxygen pressure (mm Hg) determined from modified Winkler samples collected at Rkm 14.5 (RM 9.0) on the Bighorn River during 1987.

Continuous Gas Monitoring

Measurements of gas tension by the Common Sensing tensionometer (TBO-F) at Rkm 0.6 (gagehouse) (Figures 25 and 26) usually paralleled the pattern obtained from point sampling (Figures 10 and 11) during 1987. Mean daily TGP, barometric, delta P, oxygen, and nitrogen-argon pressures measured by the Rkm 0.6 Common Sensing equipment were 789, 682, 108, 151, and 631 mm Hg, respectively. These mean values varied only 1-3 mm Hg from the point sampling measurements but should have much larger standard deviations. Calculated nitrogen-argon pressures from the two types of measurements were equal. A 2 mm Hg difference between mean barometric pressure measured by the tensionometer and the hand-held barometer was due in part to differences in the tensionometer's liquid crystal display (LCD) and values obtained through the Hydromet system. For example, on 9 July 1986, 15 measurements from the LCD readout for temperature, TGP, and oxygen pressures were 0.2 °C (±0.1), 1.4 mm Hg (±1.0), and 2.1 mm Hg (±0.6) lower than values collected by the Sutron DCP. Variations in barometric pressure between the instruments were greater than 1 mm Hg only when data were obtained via the Hydromet system.

At Rkm 4.8 (RM 3.0) the uncorrected TGP and delta P measurements from the Common Sensing meter (Figures 27 and 28) were at times substantially different than tensions measured with the Bouck gasometer (Figures 14 and 15). As a result of instrumentation problems, mean daily pressures measured by the tensionometer at Rkm 4.8 were much lower than Bouck measurements,

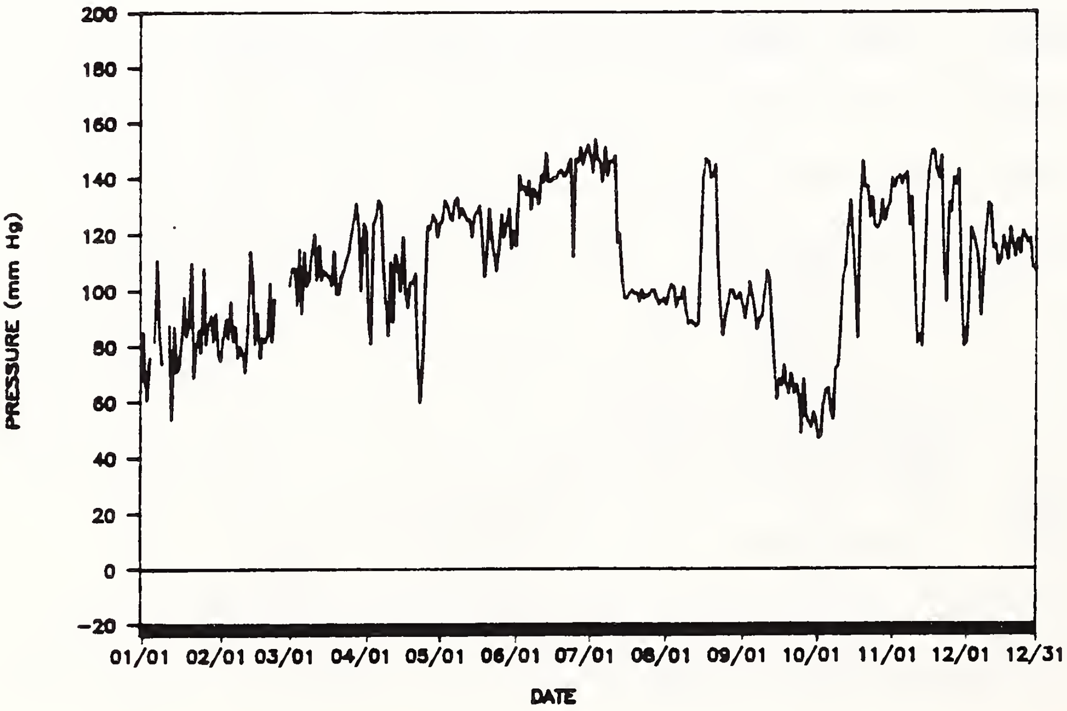


Figure 25. Uncorrected mean daily delta P (mm Hg) measured at Rkm 0.6 (gagehouse) by the Common Sensing tensionometer (Hydromet archive files) during 1987.

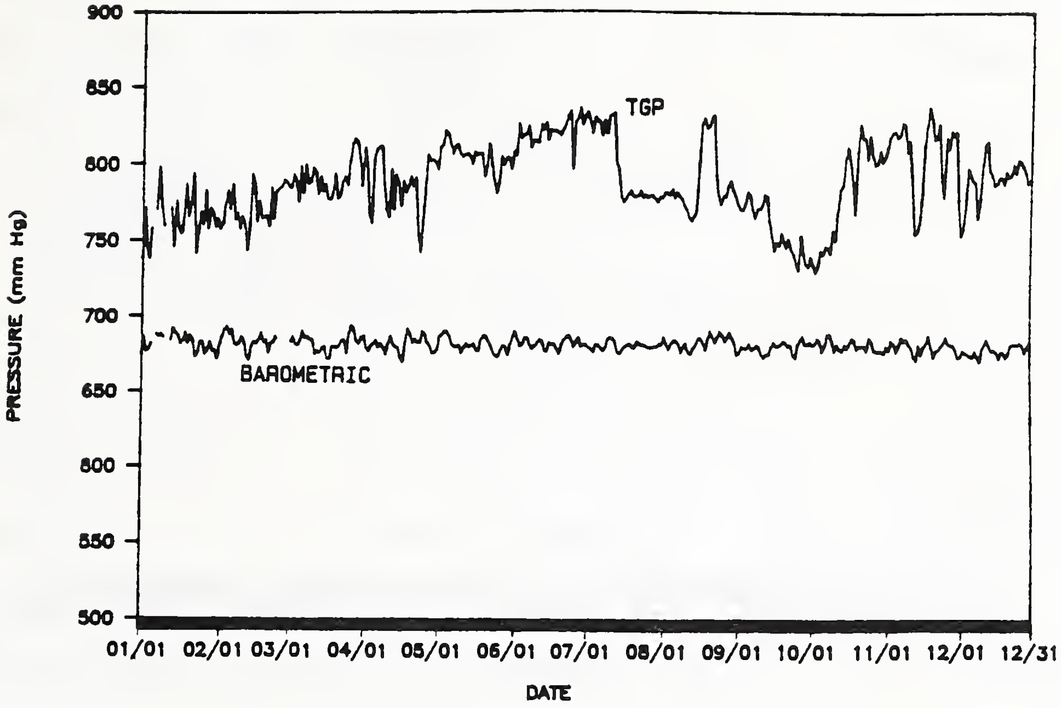


Figure 26. Uncorrected mean daily TGP and barometric pressures (mm Hg) measured at Rkm 0.6 by the Common Sensing tensionometer (Hydromet archive files) during 1987.

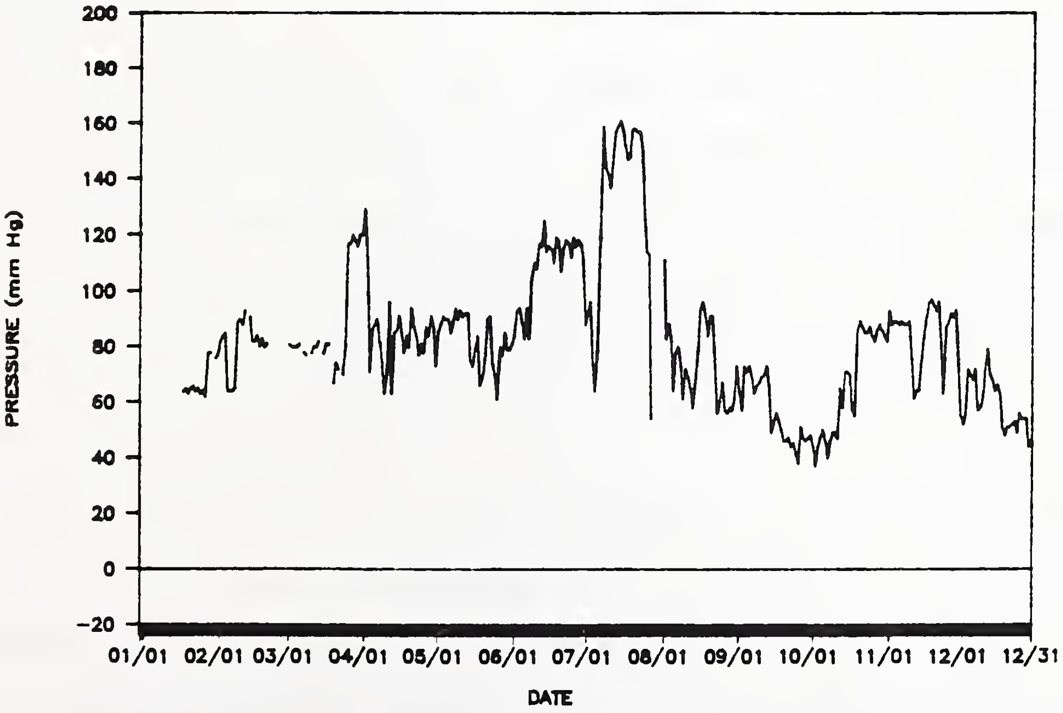


Figure 27. Uncorrected mean daily delta P (mm Hg) measured at Rkm 4.8 (RM 3.0) by the Common Sensing tensionometer (Hydromet archive files) during 1987.

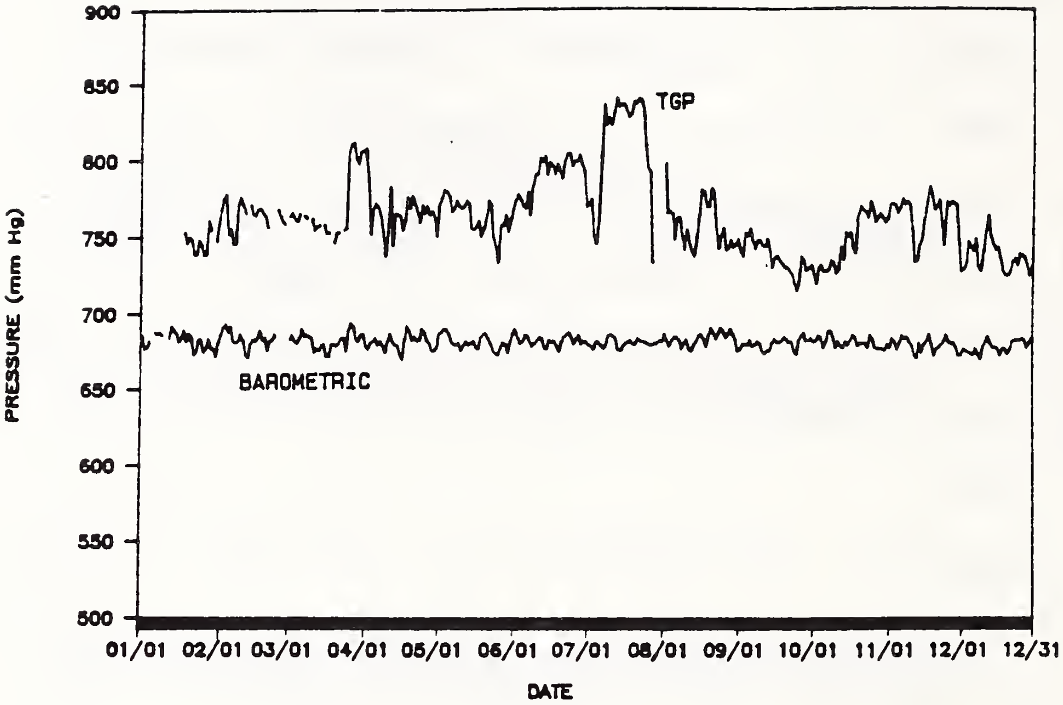


Figure 28. Uncorrected mean daily TGP at Rkm 4.8 (RM 3.0) and barometric pressure (mm Hg) at Rkm 0.6 measured by Common Sensing tensionometers (Hydromet archive files) during 1987.

particularly during late spring and early fall. Mean daily TGP, delta P, oxygen, and nitrogen-argon pressures (range in parentheses) measured at Rkm 4.8 by the tensionometer in 1987 were 764 (715-841), 82 (37-161), 179 (106-278), and 574 (426-666) mm Hg, respectively. The tensionometer mean TGP and delta P were 23 mm Hg and 25 mm Hg lower, respectively, than values found by the Bouck gasometer. Mean oxygen pressure was 14 mm Hg less than Winkler measurements, and mean nitrogen-argon pressure was 10 mm Hg lower than point estimates (Table 3). Calculated nitrogen-argon pressures determined from tensionometer data were intermediate between empirical measurements. Data collected from January - April at Rkm 4.8 were incomplete due to power supply problems.

Uncorrected oxygen pressure measured by the tensionometer at Rkm 0.6 (Figure 29) generally showed less variability, had a greater maximum, and was lower through most of the fall than Winkler measurements (Figure 20). Uncorrected tensionometer oxygen pressures measured at Rkm 4.8 (Figure 29) were even more variable than Winkler measurements (Figure 22). Variability was higher than natural flucuations due to equipment problems, which resulted in daily values as low as 106 mm Hg. The maximum daily level measured at Rkm 4.8 was 278 mm Hg on 29 July; Winklers indicate the peak was representative of actual values.

Nitrogen-argon pressures at both locations closely followed changes in TGP (Figures 30 and 31). Using the Hydromet system, nitrogen-argon pressure is calculated electronically by subtracting oxygen pressure from TGP. However, these pressures

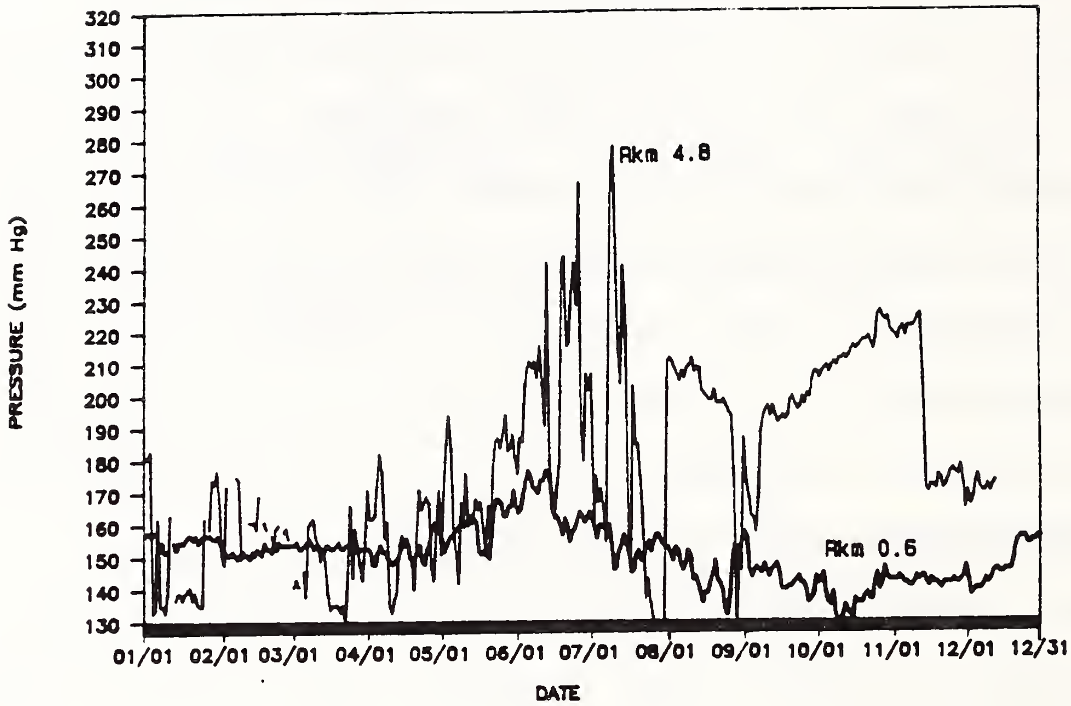


Figure 29. Uncorrected oxygen pressures (mm Hg) measured at Rkm 0.6 and Rkm 4.8 (RM 3.0) by Common Sensing tensionometers (Hydromet archive files) during 1987.

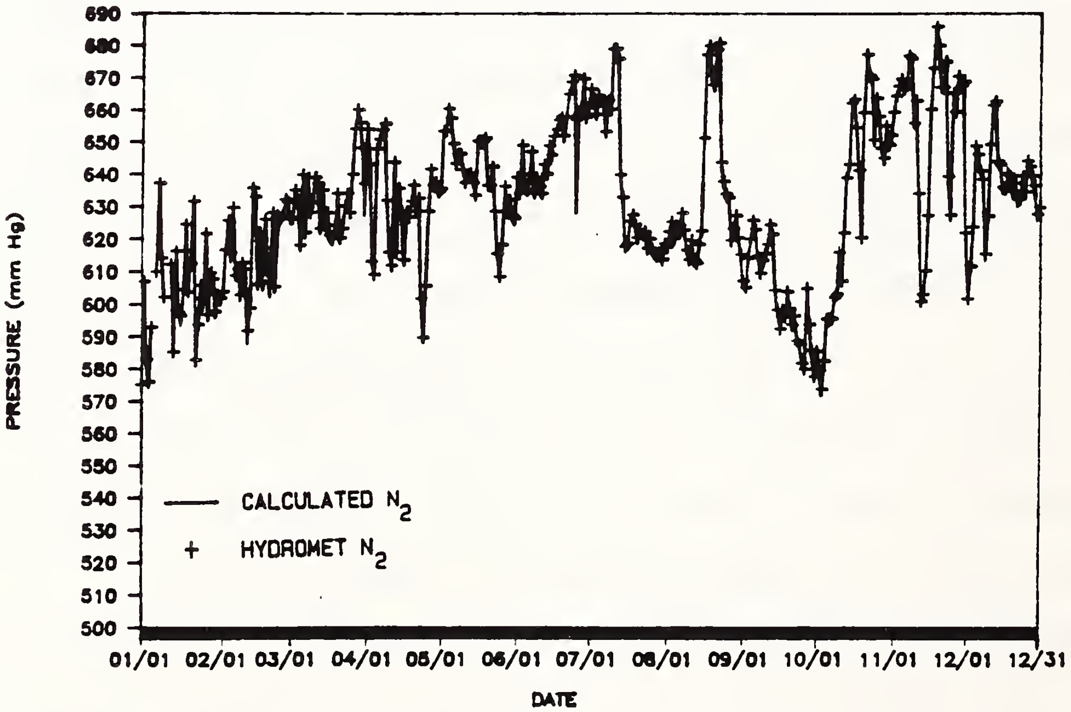


Figure 30. Uncorrected nitrogen-argon pressure minus water vapor pressure (mm Hg) measured at Rkm 0.6 (gagehouse) by the Common Sensing tensionometer (Hydromet archive files) versus calculated nitrogen-argon pressures (mm Hg) in 1987.

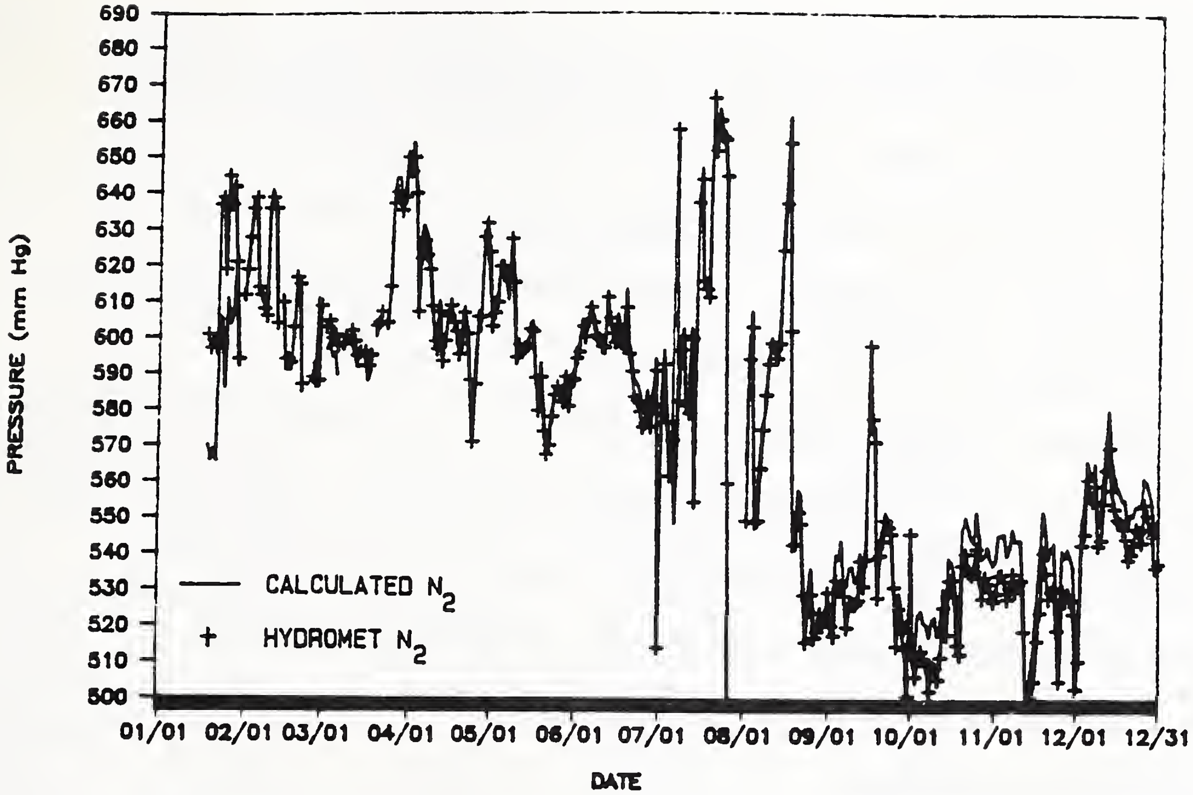


Figure 31. Uncorrected nitrogen-argon pressure minus water vapor pressure (mm Hg) measured at Rkm 4.8 (RM 3.0) by the Common Sensing tensionometer (Hydromet archive files) versus calculated nitrogen-argon pressures (mm Hg) in 1987.

can vary substantially from those determined mathematically. At Rkm 0.6 nitrogen-argon pressure readings (corrected to eliminate water vapor pressure) from the tensionometer were similar to calculated pressures (Figure 30). However, at Rkm 4.8 substantial deviations between the two were observed (Figure 31). Emphasis was placed on calibration of water temperature, TGP, oxygen, and barometric pressure data from the Sutron sites. Therefore, analysis using nitrogen-argon pressure will utilize mathematically obtained values in the future.

Calibration checks of the permanently installed tensionometers and Hydrolab 8000's were usually performed two-three times per week at both Rkm 0.6 and 4.8 (Appendix Tables 9-

12). Percent difference between tensionometer readings and manual measurements were summarized monthly (Table 4). Percentage differences in water temperature at Rkm 0.6 were highest in August and March. Large differences in August were due to a malfunction in the thermistor.

Differences between the thermometer and thermistor readings in March were slightly greater than during winter months. This is partially due to small absolute changes resulting in a relatively high percentage difference when temperatures are low. In the future we will present actual differences in addition to the percent differences.

At Rkm 0.6, the largest difference in delta P and TGP occurred in late summer and fall, during periods of lower gas pressures. Diffeneces between oxygen measurements increased during late 1987 but barometric pressure measurements were similar from the hand-held barometer and the tensionometer. Barometric pressure was measured more accurately than any other parameter. The maximum positive and negative deviations from Bouck gasometer measurements were +19 and -18 mm Hg but most differences were much smaller. The largest deviations in water temperature (excluding 21 and 24 August when the thermistor malfunctioned), oxygen, and barometric pressure were 1.1^{o}C, 23 mm Hg, and 3 mm Hg, respectively.

Maintenance of the Rkm 0.6 tensionometer included changing and cleaning the silastic tubing five times, adjustment of the TGP gain four times, oxygen pressure seven times, and barometric

Table 4. Summary of mean percent monthly differences in readings obtained using the Common Sensing Tensionometer and manual measurements at the Saint Xavier gagehouse (Rkm 0.6), Bighorn River during 1987. Standard deviations are in parentheses.

	% differences from manual:				
Month	Temperature (C)	Total gas pressure	^ P	Oxygen pressure	Barometric pressure
January	2.4(2.8)	0.5(0.3)	4.5(2.2)	2.7(1.3)	0.3(0.1)
February	3.6(2.9)	0.6(0.4)	4.1(2.8)	1.4(0.7)	0.2(0.2)
March	8.4(3.0)	0.5(0.3)	3.1(2.3)	2.5(1.8)	0.1(0.1)
April	3.9(3.7)	0.5(0.3)	3.7(2.8)	2.7(2.6)	0.1(0.1)
May	2.9(2.0)	0.6(0.6)	3.9(3.9)	3.8(2.6)	0.1(0.1)
June	2.3(1.8)	0.7(0.5)	3.9(3.0)	3.5(2.3)	0.1(0.2)
July	1.7(1.2)	0.7(0.4)	4.5(2.9)	4.1(2.3)	0.1(0.1)
August	15.3(30.4)	0.8(0.7)	6.5(6.2)	4.2(3.9)	0.1(0.1)
September	1.0(0.8)	0.6(0.7)	5.7(7.0)	3.5(1.9)	0.0(0.1)
October	0.6(0.6)	1.0(0.8)	9.3(9.3)	5.6(4.3)	0.0(0.1)
November	0.9(1.0)	0.8(0.3)	5.4(1.9)	6.4(4.5)	0.0(0.1)
December	2.2(2.3)	0.5(0.7)	3.7(5.8)	6.2(4.4)	0.0(0.1)
1987 Total	4.0(10.0)	0.6(0.5)	4.8(4.7)	3.9(3.2)	0.2(0.1)

pressure once (Appendix Table 9). Temperature gain was never adjusted at the gagehouse in 1987.

Percent differences for all parameters were much higher at Rkm 4.8 (Table 5). Temperature, TGP, delta P, and oxygen pressure differences were 1.8, 1.1, 8.4, and 11.67% more at the lower satellite station. Large differences in TGP and delta P during July were caused by damaged silastic tubing and a failed pressure transducer. The substantial differences in oxygen pressure that began in July were probably due to an oxygen sensor failure. Problems severely reduced the usefulness of most TGP and oxygen data collected at Rkm 4.8 in 1987. The maximum positive and negative deviations from Bouck measurements at Rkm

Table 5. Summary of mean percent monthly differences in readings obtained using the Common Sensing Tensionometer and manual measurements at Rkm 4.8 (RM 3.0) on the Bighorn River during 1987. Standard deviations are in parentheses.

	% error from manual:			
Month	Temperature (C)	Total gas pressure	^ P	Oxygen pressure
January	3.9(3.8)	1.3(1.0)	12.1(8.6)	8.4(13.2)
February	3.2(3.0)	2.2(0.9)	19.5(9.6)	1.8(1.4)
March	6.1(5.8)	2.7(1.2)	21.0(6.8)	4.5(5.1)
April	6.4(2.2)	1.6(1.9)	12.6(16.0)	8.4(5.1)
May	5.9(3.2)	0.8(0.7)	5.0(3.9)	6.7(4.9)
June	9.1(7.6)	1.4(1.1)	8.4(6.4)	6.6(6.4)
July	7.5(6.7)	4.1(3.5)	24.3(24.8)	25.7(20.7)
August	6.3(4.5)	1.1(0.9)	9.1(7.5)	10.7(8.2)
September	3.1(1.9)	1.3(0.6)	12.1(7.1)	16.5(12.3)
October	3.5(2.4)	1.0(0.8)	8.3(7.1)	46.3(104.9)
November	5.8(2.1)	1.4(0.9)	12.4(10.0)	29.6(10.7)
December	3.9(2.8)	1.0(0.9)	10.9(9.9)	5.6(2.3)
1987 Total	5.8(4.8)	1.8(1.9)	13.2(13.1)	15.4(34.8)

4.8 were +79 and -93 mm Hg. Maximum oxygen pressure deviations were as great as -188 and +743 mm Hg and temperature differences were as high as 2.2°C.

A greater number of gain adjustments were necessary at Rkm 4.8. TGP, OP, and temperature gain were adjusted 19, 20, and 9 times, respectively. Silastic tubing was changed five times and the complete tensionometer was replaced twice (12 January and 3 August).

Oxygen pressure at Rkm 4.8 in 1987 and previous years has been the most variable parameter (Appendix Table 11). Elsewhere, most tensionometer problems have also related to oxygen probe drifting or failing (COE 1986 and 1987). It appears that failure of the Leeds and Northrup probe or the oxygen circuit board are common after 3 years and perhaps much sooner. Moisture accumulation in the electronics, allowing current leakage may ultimately short out the sensor resulting in failure (COE 1986 and 1987). Current leakage could be contained by coating the circuit boards with urethane insulating spray, installing a small-wattage heater at the station, and monitoring current leakage on at least a 6 month basis (COE 1986 and 1987). Only tensionometers with urethane coated circuit boards should be installed at the Rkm 4.8 site in the future,. Also, a method for providing heat in the enclosure containing the control boxes and DCP should be found if continuous, long term operation from the oxygen sensor is expected.

A comparison of percent differences between Common Sensing tensionometers and manual measurements at 13 sites on the Columbia and Snake River drainages and on the Bighorn River shows that readings were less variable on the Bighorn than at other sites (Table 6). Delta P differences for all stations were 54.2% and 61.2% in 1986 and 1987, respectively; this was much larger than the 4.8% variation at Rkm 0.6 or 13.2% at Rkm 4.8.

The gagehouse (Rkm 0.6) Hydrolab 8000 displayed a consistent difference between a laboratory thermometer and its unadjustable thermistor; the average difference was $-1.1^{o}C \pm 0.9$. As found with the tensionometers, the liquid crystal display (LCD) readout provided lower values than those transmitted over the Hydromet system. Hydromet data were always more than $3^{o}C$ greater than

Table 6. Summary of mean annual differences in readings from comparisons of Common Sensing Tensionmeters and manual measurements at 13 Telemetry stations on the Columbia and Snake River drainages. (COE 1986 and 1987).

	% error from manual:									
Year	Temperature (C)		Total gas pressure		^ P		Oxygen pressure		Barometric pressure	
	N	%	N	%	N	%	N	%	N	%
Lower Granite Dam Forebay - Station 1205										
1986	0.25	2.04	25.25	3.17	25.00	56.58	13.25	8.83	2.00	0.27
1987	0.93	6.53	13.17	1.69	13.83	38.18	13.33	8.69	2.00	0.27
Little Goose Dam Forebay - Station 1118										
1986	0.17	1.27	30.80	3.92	17.00	78.77	-	-	5.25	0.70
1987	0.62	3.05	11.25	1.52	26.25	111.72	-	-	1.17	0.16
Lower Monumental Dam Forebay - Station 1018										
1986	0.51	3.68	27.83	3.53	15.67	188.37	14.80	9.56	2.33	0.31
1987	0.37	1.73	28.0	3.62	48.33	110.00	10.33	7.35	1.17	0.16
Ice Harbor Dam Forebay - Station 916										
1986	0.25	1.88	8.67	1.05	9.00	43.63	16.80	11.51	2.50	0.33
1987	0.36	1.84	26.25	3.31	28.25	270.06	10.00	5.97	1.71	0.23
McNary Dam Forebay, Oregon - Station 820										
1986	0.53	3.86	18.25	2.14	15.00	14.71	-	-	1.00	0.13
1987	0.50	2.84	11.75	1.43	11.00	16.20	27.60	16.26	1.00	0.13
McNary Dam Forebay, Washington - Station 814										
1986	0.87	4.51	53.33	6.11	53.33	48.12	23.80	13.93	0	0
1987	0.45	2.67	11.60	1.45	14.25	32.18	17.00	9.85	0.68	0.09
John Day Dam Forebay - Station 3757										
1986	0.35	2.32	1.50	0.19	1.00	1.85	8.20	5.09	1.50	0.20
1987	0.90	5.06	15.30	1.89	19.33	37.85	6.00	4.08	3.00	0.40
The Dalles Dam Forebay - Station 3700										
1986	0.47	3.06	5.33	0.65	5.33	55.68	-	-	0	0
1987	0.38	2.03	13.75	1.75	15.25	72.79	-	-	1.50	0.2
Bonneville Dam Forebay - Station 462										
1986	0.43	2.66	24.50	3.01	26.00	68.16	-	-	1.33	0.27
1987	0.31	2.12	84.00	10.98	15.30	93.02	-	-	1.00	0.13
Warrendale, Oregon - Station 356										
1986	0.07	0.62	17.00	2.01	15.30	30.66	61.75	37.29	2.50	0.33
1987	0.47	2.84	6.20	0.79	6.00	36.50	12.57	8.13	0.83	0.11

Table 6. (continued).

Year	Temperature (C)		Total gas pressure		^ P		Oxygen pressure		Barometric pressure	
	% error from manual:									
	N	%	N	%	N	%	N	%	N	%
Chief Joseph Dam Forebay - Station 2512										
1986	0.58	6.72	35.25	4.21	29.67	31.52	27.50	17.60	2.00	0.27
1987	0.32	1.94	6.75	0.84	7.00	9.46	23.50	15.26	1.20	0.16
Columbia River International Boundary - Station 2830										
1986	0.40	4.14	3.00	0.36	6.50	6.27	4.00	2.36	7.00	0.95
1987	0.07	0.40	5.75	0.65	6.00	4.31	31.00	17.75	-	-
Grand Coulee Dam - downstream 6 miles - Station 2616										
1986	0.20	1.16	11.67	1.43	7.00	8.79	41.00	26.80	-	-
1987	0.07	0.40	5.75	0.65	1.50	2.00	31.00	17.75	-	-
Total - All Stations										
1986	0.40	2.95	22.32	2.72	18.59	54.16	22.20	13.91	2.36	0.31
1987	0.47	2.77	17.44	2.23	14.23	61.22	16.50	10.25	1.42	0.19

manual measurements, while LCD readings were lower than manual measurements and never varied more than 1.3^{o}C from the thermometer values. If elevation of other parameters stored by the Hydromet system occurs, correction factors will be applied. Hydrolab oxygen pressures compared to a Winkler at the beginning and end of a 30 min period showed differences were highly variable, ranging from +149 to -118 mm Hg. These differences were greater than for the Common Sensing meter, so data collected from the tensionometer were used rather than Hydrolab data. Temperature data transmission from the Hydrolab interferred with data collection and analysis of daily mean water temperatures from the Common Sensing meter, so collection of water temperature and dissolved oxygen from the Hydrolab was discontinued; however, conductivity and pH data continue to be collected from the Hydrolab.

Early in the year, a power supply problem resulted in data collection and transmission occurring sporadically at Rkm 4.8; this was corrected on 25 March. Even after continuous power was restored, comparisons showed measurements were more variable compared to manual measurements than at Rkm 0.6. The mean difference between water temperature measured by the Hydrolab 8000 at Rkm 4.8 and a laboratory thermometer was 3.2°C ±5.4. Large differences between water temperatures during late 1987 were due to water leakage and corrosion of connectors in buried cable. The Hydrolab provided inconsistent oxygen readings that varied substantially during 30 min calibration periods. Membranes on Hydrolab oxygen sensors quickly foul and are a poor choice for continuous long term monitoring instruments unless frequent maintenance can occur.

Recurring problems at Rkm 4.8 that involved the power supply, a ground loop between the two instruments, interfacing incompatibilities between Hydrolab and Sutron equipment, and calibration problems with some Hydrolab parameters minimized reliability of most data. The ground loop was found and eliminated in 1988. Also, the apparent failure of Leeds and Northrup oxygen probes on two tensionometers at the site minimzes confidence in oxygen data collected during a substantial portion of the year.

Downriver Gas Test

During August 1987, gas tensions were measured through-out the study area on both sides of the river while Afterbay Dam was operated under two different regimes. On 16 August, pressures were measured between Afterbay Dam and Rkm 12.9 while only radial gates discharged water; all five radial gates were open 0.94-1.0 ft and this resulted in relatively low hyperbaric pressures. TGP and delta P were similar near both banks at each site and increased slightly in a downstream direction (Table 7). Mean TGP was 772 mm Hg along the left bank while on the right bank it was 774 mm Hg. Minimum and maximum TGP and delta P values on both banks were measured at Rkm 3.2 and 11.3, respectively, and pressures varied over a range of 36 mm Hg on the right bank and 26 mm Hg on the left bank. The maximum TGP of 788 mm Hg represented a delta P of 108 mm Hg and was about 20 mm Hg less than the cardiovascular system threshold for bubble formation.

Oxygen pressures on both banks increased about 65 mm Hg from a minimum near 140 mm Hg at the gagehouse to peak levels at Rkm 11.3. Calculated nitrogen and argon pressure was highest in the uppermost reach of the river. Water temperature warmed approximately 2.5^{o}C along both between Rkm 0.6 and Rkm 12.9. These data indicate that gas pressures remained relatively low and constant both across and downriver when only the radial gates were used to discharge 59.44 m^3/s (2099 cfs). A similar sampling run on 18 July, 1986, when only radial gates were passing water and discharge was 177.34 m^3/s (6262 cfs), showed larger variation in gas pressures between banks and through the study

Table 7. Downriver gas dissipation test on the Bighorn River downstream from Afterbay Dam on 16 August, 1987. (Q= 2099 cfs; sluiceway gates closed, opening of radial gates 1, 3, + 5 = 1.0 ft.; mean opening of radial gates 2 + 4 = 0.94 ft.; weather = mostly cloudy until 14:05, then clearing).

Rkm	Bank[a]	Time	TGP mm Hg	^P mm Hg	$P\text{-}O_2$ mm Hg	$P\text{-}N_2$[b] mm Hg	Temperature (C)
0.6	R	9:40	767	82	140	616	12.2
0.6	L	9:55	763	83	141	611	12.3
0.8	L	10:10	767	88	152	604	12.4
0.8	R	10:23	766	86	148	607	12.4
1.6	L	10:41	769	89	158	600	12.5
1.6	R	10:55	762	82	147	604	12.4
2.4	R	11:16	761	81	149	601	12.4
2.4	L	11:29	766	86	160	595	12.5
3.2	R	12:35	752	71	153	588	12.8
3.2	L	12:49	762	82	171	580	13.4
4.0	R	13:04	763	83	183	569	13.1
4.0	L	13:16	763	83	186	565	13.5
4.8	R	13:33	763	83	190	561	13.6
4.8	L	13:49	769	89	187	570	13.7
6.4	L	14:05	774	94	187	575	13.4
6.4	R	14:19	776	96	183	582	13.3
8.0	R	14:35	774	94	191	571	13.8
8.0	L	14:48	781	101	193	576	13.7

a - R = right bank, L = Left Bank

b - Nitrogen and argon values are calculated and do not represent empirical measurements from the tensionometer.

Table 7. (continued).

Rkm	Bank[a]	Time	TGP mm Hg	^P mm Hg	$P-O_2$ mm Hg	$P-N_2$[b] mm Hg	Temperature (C)
9.7	R	15:07	778	98	200	566	14.3
9.7	L	15:21	785	105	203	570	14.4
11.3	L	15:45	788	108	207	568	14.8
11.3	R	15:55	788	107	205	570	14.6
12.9	R	16:07	787	106	197	577	14.8
12.9	L	16:18	780	99	201	566	14.8

a - R = right bank, L = Left Bank

b - Nitrogen and argon values are calculated and do not represent empirical measurements from the tensionometer.

area. Although hyperbaric pressures were not critically high during either test, this demonstrates that changes in TGP occur due to variations of discharge, river elevation, water temperature, weather conditions, etc., even during the same operational mode.

On 22 August, 1987, the downriver gas pressures and temperature were measured during a period when only the sluiceway gates were releasing water and discharge was 62.16 m^3/s (2195 cfs). The mean delta P increased 17 and 20 mm Hg over levels measured 6 d before, to 106 and 112 mm Hg on the right and left banks, respectively (Table 8). Corresponding mean TGP's were 797 and 803 mm Hg, respectively. Maximum delta P's were 140 and 145 mm Hg on the right and left banks at Rkm 2.4, respectively. Maximum TGP was 22 and 18 mm Hg greater on the right and left banks, respectively, than the threshold for bubble formation in the cardiovascular system. As on 16 August, each parameter exhibited the same general pattern on both banks. The pattern of TGP, delta P and $P\text{-}O_2$, however, was different between tests. Gas entrainment by the sluiceway gates produced higher TGP's and delta P's in the upper portion of the study area with pressures decreasing substantially downstream. TGP at Rkm 11.3 and at the next downstream station appeared to be unaffected by the operational changes.

Failure of oxygen probes on both tensionometers prevented the determination of oxygen and nitrogen and argon pressures

Table 8. Downriver gas dissipation test on the Bighorn River downstream from Afterbay Dam on 22 August, 1987. ($\bar{Q}$= 2195 cfs; mean opening of sluiceway gates 1, 2, and 3 = 2.56, 2.50, and 2.50, respectively; all radial gates closed; weather = partly or mostly cloudy except between 14:05 - 15:58 when sunny or mostly sunny conditions prevailed).

Rkm	Bank[a]	Time	TGP mm Hg	^P mm Hg	$P\text{-}O_2$ mm Hg	$P\text{-}N_2$[b] mm Hg	Temperature (C)
0.6	R	11:32	816	123	144	661	13.0
0.6	L	11:54	820	127	149	660	13.1
0.8	L	12:16	828	136	149	667	13.4
0.8	R	12:31	827	135	140	675	13.4
1.6	R	12:48	823	131	152	659	13.5
1.6	L	13:00	829	137	162	655	14.1
2.4	L	13:16	837	145	176	649	14.3
2.4	R	13:31	832	140	165	655	13.9
3.2	R	13:49	809	117	173	624	14.6
3.2	L	14:05	813	121	188	612	15.6
4.0	R	14:22	811	120	180	618	14.8
4.0	L	14:38	811	120	180	618	15.2
4.8	L	14:55	814	123	191	609	16.1
4.8	R	15:22	805	114	191	600	16.0
6.4	R	15:43	820	129	172	635	15.3
6.4	L	15:58	821	130	170	638	15.1
8.0	L	16:17	817	126	172	632	15.3
8.0	R	16:31	808	117	168	627	15.6

a - R = right bank, L = Left Bank

b - Nitrogen and argon values are calculated and do not represent empirical measurements from the tensionometer.

Table 8. (continued).

Rkm	Bank[a]	Time	TGP mm Hg	^P mm Hg	P-O$_2$ mm Hg	P-N$_2$[b] mm Hg	Temperature (C)
9.7	R	17:01	800	109	155	631	15.9
9.7	L	17:15	798	107	134	650	15.8
11.3	L	17:36	789	100	-	-	16.2
11.3	R	17:51	789	98	-	-	15.9
12.9	R	18:11	787	96	-	-	16.5
12.9	L	18:22	785	97	-	-	16.0
14.5	R	18:45	778	90	-	-	16.3
14.5	L	19:00	771	82	-	-	16.0
16.1	R	19:21	764	75	-	-	16.2
16.1	L	19:36	759	70	-	-	15.6
17.7	R	19:53	750	59	-	-	16.0
17.7	L	20:05	747	56	-	-	15.8
19.3	R	20:23	736	45	-	-	16.2

a - R = right bank, L = Left Bank

b - Nitrogen and argon values are calculated and do not represent empirical measurements from the tensionometer.

downstream from Rkm 9.7. In the upper reach of the study area, oxygen pressure achieved maximum levels at Rkm 4.8 and then declined. Maximum levels were not as high as on 16 August, probably due to differences in solar insolation and the time of day when measurements were made. As on 16 August, water temperature increased in a downstream direction and was nearly the same on both sides of the river; mean water temperature was 1.8°C higher on 22 August than on 16 August.

Afterbay Reservoir Gas Monitoring

A Commom Sensing tensionometer was used to measure gas tensions in Afterbay Reservoir 10 times from 8 May - 30 July, 1987 (Table 9). Unlike delta P's from the irrigation canal and Afterbay Reservoir in 1986, all values were positive with a mean value of 28 mm Hg and a range of 3-47 mm Hg. Mean TGP was 706 mm Hg (range = 687-722), the average oxygen pressure was 134 mm Hg (range = 119-145), and the mean calculated nitrogen and argon pressure was 565 mm Hg (range = 543-580). Oxygen saturation levels on all but two occasions remained just below equilibrium while both TGP and nitrogen and argon saturation was always slightly higher than equilibrium with atmospheric pressure. Oxygen levels remained substantially higher than 1986 measurements in both the irrigation canal and Afterbay Reservoir. Gas levels in Afterbay Reservoir apparently can flucuate greatly and probably depend upon conditions in Bighorn Lake and the river upstream.

Cross River Transects

Measurements of hyperbaric pressures at Rkm 0.6 when the sluiceway gates were closed showed relatively little change across the river (Table 10). Mean delta P was 82 mm Hg, and excluding the 3.0 m reading, varied only 8 mm Hg. Nitrogen and argon pressure fluctuated slightly, while oxygen tensions increased 14 mm Hg from 6.1 - 51.8 m along the transect. Further downstream, cross river transects showed that at the same

Table 9. Gas tensions (mm Hg) measured at the boat ramp on Afterbay Reservoir from 8 May - 30 July, 1987.

Date	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
5/8	14:56	698(23)	134	557	7.1	6.1
5/22	14:39	722(39)	136	580	6.8	5.6
5/29	16:38	704(28)	138	558	7.1	6.1
6/5	14:20	703(25)	134	562	6.8	5.6
6/17	17:07	722(47)	142	572	7.8	7.5
6/29	11:25	687(3)	137	543	7.1	6.1
7/3	10:06	710(33)	145	558	7.0	5.9
7/9	16:50	711(35)	127	577	7.6	7.2
7/17	13:42	700(23)	119	573	8.3	8.4
7/30	19:11	701(25)	125	568	8.7	9.2
Mean		706(28)	134	565	7.4	6.8
Std dev.		11	8	11	0.7	1.3

Table 10. Cross river transect of gas tensions at Rkm 0.6 on 12 August, 1987. (Q = 2119 cfs: range = 2099-2145 cfs; mean barometric pressure = 681 mm Hg, sluiceway gates closed, radial gates 1, 3,& 5 open 1.0 ft and mean opening of radial gates 2 & 4 = 1.40 and 1.39 ft, respectively; range = 1.07-1.78 ft, weather = mostly clear or sunny).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	14:40	749(68)	134	604	10.7	12.2
6.1(20)	15:00	759(78)	132	616	10.5	12.0
9.1(30)[c]	15:11	761(80)	132	618	10.5	12.0
12.2(40)	15:22	764(83)	133	620	10.6	12.1
15.2(50)	15:33	763(82)	134	618	10.6	12.1
18.3(60)	15:44	763(82)	136	616	10.6	12.1
21.3(70)	15:55	763(82)	137	615	10.7	12.2
24.4(80)	16:06	762(81)	138	613	10.7	12.2
27.4(90)	16:18	763(83)	138	614	10.7	12.3
30.5(100)	16:30	763(83)	139	613	10.7	12.3
33.5(110)	16:41	763(83)	138	614	10.8	12.4
36.6(120)	16:52	763(83)	138	614	10.9	12.5
39.6(130)	17:03	763(83)	140	612	10.9	12.5
42.7(140)	17:14	762(82)	140	611	10.9	12.6
45.7(150)	17:25	764(84)	141	612	10.9	12.6
48.8(160)	17:36	764(84)	143	610	11.0	12.7
51.8(170)	17:47	766(86)	146	609	11.2	12.9

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.
c - in line with continuous monitoring probe.

approximate discharge and with sluiceway gates closed, delta P was higher and more variable (Tables 11 and 12). At Rkm 4.8, mean delta P was 104 mm Hg and ranged from 91-113 mm Hg. Nitrogen and argon pressure was highest in mid-channel; oxygen pressure was greatest near the left bank. The mean delta P determined from all measurements at Rkm 14.9 on 14 August was 96 mm Hg and values varied over a 70 mm Hg range. The cross river transect at the lower station was located at Rkm 14.9 rather than at Rkm 14.5 because of problems anchoring the boat at the long term gas monitoring site. The low delta P at Rkm 14.9 was probably related to a severe thunderstorm that reduced photosynthesis and probably increased reaeration. If measurements made after the storm (later than 17:14) are excluded, the mean delta P increased to 114 mm Hg and the range decreased to 33 mm Hg. Oxygen pressure before the storm tended to be greater than 200 mm Hg and unlike all upstream transects, nitrogen and argon pressures were less than 600 mm Hg.

Although maximum TGP increased at each downstream transect, no maximum TGP was higher than the threshold for bubble growth in the cardiovascular system of fish at the water surface. However, the difference between the maximum TGP and the threshold decreased from 33 mm Hg at Rkm 0.6 to 11 mm Hg at Rkm 4.8 and only 2 mm Hg at Rkm 14.9.

Mean delta P at Rkm 0.6 measured on 12 August when the sluiceway was not in use was intermediate between delta P levels determined from two profiles done in 1986. Based on cross-river transect data, which were collected when water temperatures

Table 11. Cross river transect of gas tensions at Rkm 4.8 on 13 August, 1987. (Q = 2079 cfs: range = 2043-2110 cfs; mean barometric pressure = 675 mm Hg, sluiceway gates closed, radial gates 1, 3,& 5 open 1.0 ft and mean opening of radial gates 2 & 4 = 1.09 and 1.07 ft, respectively; range = 1.05-1.18 ft, weather = cool, mostly sunny until 14:00, then mostly cloudy).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	12:00	772(96)	182	578	11.7	13.6
6.1(20)	12:15	778(102)	176	591	11.2	12.9
9.1(30)[c]	12:27	782(106)	176	595	11.1	12.8
12.2(40)	12:46	786(110)	174	601	10.9	12.6
15.2(50)	12:59	787(111)	172	604	10.9	12.5
18.3(60)	13:11	787(111)	171	605	10.7	12.3
21.3(70)	13:28	785(109)	163	611	10.7	12.2
24.4(80)	13:48	782(106)	160	611	10.6	12.1
27.4(90)	14:18	774(98)	156	608	10.4	11.9
30.5(100)	14:30	773(97)	154	609	10.4	11.9
33.5(110)	14:43	774(99)	156	608	10.4	11.9
36.6(120)	14:55	777(103)	177	589	10.5	12.0
39.6(130)	15:10	780(106)	177	592	10.6	12.1
42.7(140)	15:22	781(106)	179	591	10.6	12.1
45.7(150)	15:34	783(109)	181	591	10.7	12.3
48.8(160)	15:50	787(113)	184	592	10.8	12.4
51.8(170)	16:02	786(112)	185	590	10.9	12.5
54.9(180)	16:15	787(113)	186	590	10.9	12.6

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.
c - in line with continuous monitoring probe.

Table 11. (continued).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
57.9(190)	16:35	782(109)	202	569	11.0	12.7
61.0(200)	16:48	780(107)	203	566	11.1	12.8
64.0(210)	17:01	775(102)	202	562	11.1	12.8
67.1(220)	17:17	774(100)	204	559	11.2	12.9
70.1(230)	17:29	772(99)	204	557	11.4	13.2
73.2(240)	17:41	769(95)	206	551	11.9	13.9
76.2(250)	17:55	764(91)	205	547	12.3	14.4

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.

Table 12. Cross river transect of gas tensions at Rkm 14.9 on 14 August, 1987. (Q = 2086 cfs: range = 2054-2110 cfs; mean barometric pressure = 675 mm Hg, sluiceway gates closed, radial gates 1, 3,& 5 open 1.0 ft and mean opening of radial gates 2 & 4 = 0.94 and 0.93 ft, respectively; range = 0.85-1.04 ft, weather = mostly sunny until 15:00, then cloudy until rain at 17:45, mostly cloudy afterward).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	14:39	795(121)	200	583	12.5	14.6
6.1(20)	14:51	797(122)	204	580	12.5	14.7
9.1(30)[c]	15:03	799(125)	207	579	12.7	14.9
12.2(40)	15:15	800(125)	208	579	12.8	15.0
15.2(50)	15:27	800(125)	207	580	12.8	15.0
18.3(60)	15:39	798(123)	205	580	12.8	15.0
21.3(70)	15:53	796(122)	205	578	12.8	15.0
24.4(80)	16:03	794(119)	204	577	12.8	15.0
27.4(90)	16:13	791(116)	202	576	12.8	15.0
30.5(100)	16:22	788(113)	200	575	12.8	15.0
33.5(110)	16:32	784(109)	202	569	12.8	15.0
36.6(120)	16:40	783(108)	203	567	12.7	14.9
39.6(130)	16:48	781(106)	202	566	12.7	14.9
42.7(140)	16:56	778(103)	200	565	12.7	14.9
45.7(150)	17:06	773(98)	196	564	12.6	14.8
48.8(160)	17:14	768(92)	192	563	12.6	14.8
51.8(170)	17:49	744(69)	197	535	12.4	14.5
54.9(180)	17:58	744(69)	194	538	12.3	14.4

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.
c - in line with continuous monitoring probe.

Table 12. (continued).

Location[a] m(ft)	Time	Pressure (mm Hg) Total(^P)	O_2	N_2+Ar[b]	Water Vapor	Temperature (C)
57.9(190)	18:07	742(67)	192	538	12.3	14.4
61.0(200)	18:15	740(65)	180	548	12.3	14.4
64.0(210)	18:22	738(63)	192	534	12.3	14.4
67.1(220)	18:33	734(59)	198	524	12.2	14.3
70.1(230)	18:41	733(58)	202	519	12.2	14.3
73.2(240)	18:49	732(57)	202	518	12.3	14.4
76.2(250)	18:56	730(55)	197	521	12.5	14.6

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.

ranged from about 12-19°C and discharges ranged from 59.47-163.29 m^3/s (2100-5766 cfs), maximum delta P would be under 100 mm Hg regardless of water temperature and discharge. Mean delta P levels would range from approximately 70-90 mm Hg when water is discharged only over the radial gates of Afterbay Dam.

The same transects were remeasured 6 d later when only the sluiceway gates were used to release water from Afterbay Reservoir (Tables 13, 14, and 15). Although discharge remained near 59.47 m^3/s (2100 cfs), hyperbaric pressures showed major increases. The largest increase in the mean and maximum delta P was 58 and 63 mm Hg, respectively at Rkm 0.6. The rise of 18 and 24 mm Hg in mean delta P values at Rkm 4.8 and 14.9, respectively, was substantially lower than immediately below Afterbay Dam but still represented potentially negative impacts

Table 13. Cross river transect of gas tensions at Rkm 0.6 on 18 August, 1987. (Q = 2093 cfs: range = 2065-2122 cfs; mean barometric pressure = 686 mm Hg, mean opening of sluiceway gates 1, 2, & 3 = 2.37, 2.37, and 2.35 ft, respectively; range = 2.31-2.46 ft, all radial gates closed, weather = sunny and clear).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	14:47	821(135)	147	663	11.2	13.0
6.1(20)	15:00	829(143)	150	668	11.1	12.8
9.1(30)[c]	15:13	826(140)	149	666	11.0	12.7
12.2(40)	15:27	826(140)	148	667	10.9	12.6
15.2(50)	15:39	833(147)	147	675	10.9	12.5
18.3(60)	15:57	832(146)	145	676	10.9	12.5
21.3(70)	16:09	835(149)	145	679	10.9	12.6
24.4(80)	16:21	833(147)	145	677	10.9	12.6
27.4(90)	16:32	832(146)	145	676	10.9	12.6
30.5(100)	16:44	832(146)	146	675	10.9	12.6
33.5(110)	16:55	828(144)	145	672	10.9	12.6
36.6(120)	17:07	826(142)	145	670	10.9	12.6
39.6(130)	17:19	824(138)	145	668	10.9	12.6
42.7(140)	17:30	822(136)	145	666	10.9	12.6
45.7(150)	17:44	821(135)	145	665	10.9	12.6
48.8(160)	17:55	819(133)	151	657	10.9	12.6
51.8(170)	18:07	805(119)	149	645	11.1	12.8

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.
c - in line with continuous monitoring probe.

Table 14. Cross river transect of gas tensions at Rkm 4.8 on 19 August, 1987. (Q = 2098 cfs: range = 2054-2133 cfs; mean barometric pressure = 683 mm Hg, mean opening of sluiceway gates 1, 2, & 3 = 2.22, 2.20, and 2.19 ft, respectively; range = 2.33-2.13 ft, all radial gates closed, weather = sunny and clear until 17:00, then high scattered clouds).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	12:07	793(109)	196	585	12.5	14.6
6.1(20)	12:19	798(114)	194	592	12.3	14.4
9.1(30)	12:32	805(121)	193	600	11.9	13.9
12.2(40)	12:52	809(125)	194	603	12.0	14.0
15.2(50)	13:05	812(128)	192	608	11.9	13.9
18.3(60)	13:17	814(131)	187	615	11.8	13.7
21.3(70)	13:35	816(133)	186	618	11.8	13.7
24.4(80)	13:48	817(133)	183	622	11.8	13.7
27.4(90)	14:03	816(132)	184	620	11.8	13.7
30.5(100)	14:18	818(134)	184	622	11.8	13.7
33.5(110)	14:32	819(135)	185	622	11.8	13.8
36.6(120)	14:46	820(137)	185	623	11.8	13.8
39.6(130)	15:00	818(135)	188	618	11.9	13.9
42.7(140)	15:12	818(135)	187	619	12.0	14.0
45.7(150)	15:26	817(134)	212	593	12.0	14.0
48.8(160)	15:42	816(133)	215	589	12.0	14.0
51.8(170)	15:56	813(130)	208	593	12.0	14.0
54.9(180)	16:09	811(128)	193	606	12.0	14.0

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.

Table 14. (continued).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
57.9(190)	16:31	810(127)	209	589	12.0	14.0
61.0(200)	16:44	808(125)	210	586	12.0	14.0
64.0(210)	17:05	804(122)	217	575	12.1	14.1
67.1(220)	18:06	792(109)	198	582	11.8	13.8
70.1(230)	18:18	788(106)	196	580	11.8	13.8
73.2(240)	18:30	785(103)	194	579	11.8	13.8
76.2(250)	18:46	779(97)	190	577	11.9	13.9
79.2(260)	18:59	771(89)	188	571	12.0	14.0
82.3(270)	19:12	764(82)	188	564	12.2	14.3

a - distance from right bank when facing downstream.

b - nitrogen and argon pressures are calculated values.

Table 15. Cross river transect of gas tensions at Rkm 14.9 on 20 August, 1987. (Q = 2101 cfs: range = 2087-2110 cfs; mean barometric pressure = 677 mm Hg, mean opening of sluiceway gates 1, 2, & 3 = 2.17, 2.18, & 2.13 ft, respectively; range = 2.13-2.19 ft, all radial gates closed, weather = sunny and clear until 17:00, then sunny with high, thin clouds).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
0.0(0)	13:29	794(116)	218	563	13.0	15.3
3.0(10)	13:41	798(120)	221	564	13.1	15.4
6.1(20)	13:53	800(122)	211	576	13.2	15.5
9.1(30)	14:05	802(124)	213	576	13.4	15.7
12.2(40)	14:23	806(128)	221	572	13.5	15.8
15.2(50)	14:35	805(127)	224	567	13.6	16.0
18.3(60)	14:49	806(129)	228	564	13.7	16.1
21.3(70)	15:06	807(130)	232	561	13.8	16.2
24.4(80)	15:14	807(130)	234	559	13.8	16.2
27.4(90)	15:24	808(131)	228	566	13.8	16.2
30.5(100)	15:34	807(130)	220	573	13.8	16.2
33.5(110)	15:42	806(129)	218	574	13.8	16.2
36.6(120)	15:52	805(128)	215	576	13.8	16.2
39.6(130)	16:02	803(126)	209	580	13.8	16.2
42.7(140)	16:13	803(126)	201	588	13.8	16.2
45.7(150)	16:23	803(127)	224	565	13.9	16.3
48.8(160)	16:32	802(126)	211	577	13.9	16.3
51.8(170)	16:42	801(125)	213	574	13.9	16.3
54.9(180)	16:56	799(121)	194	591	13.9	16.3

a - distance from right bank when facing downstream.

b - nitrogen and argon pressures are calculated values.

Table 15. (continued).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
57.9(190)	17:03	797(119)	193	590	13.9	16.3
61.0(200)	17:12	796(118)	193	589	13.9	16.3
64.0(210)	17:24	794(116)	186	594	13.9	16.3
67.1(220)	17:32	792(114)	193	585	13.9	16.3
70.1(230)	17:40	790(112)	194	582	13.9	16.3
73.2(240)	18:00	783(105)	191	578	13.8	16.2
76.2(250)	18:07	781(103)	191	576	13.8	16.2
79.2(260)	18:13	778(100)	187	577	13.9	16.3
82.3(270)	18:23	775(97)	186	575	14.0	16.4
85.3(280)	18:29	773(95)	192	567	14.2	16.6

a - distance from right bank when facing downstream.
b - nitrogen and argon pressures are calculated values.

for trout. Maximum TGP at each site was greater than all threshold criteria for bubble formation. Maximum TGP was 31, 13, and 1 mm Hg above the highest threshold, which describes gas tensions at which bubble growth in the vascular system would occur, at Rkm 0.6, 4.8, and 14.9, respectively.

At Rkm 0.6, mean TGP increased 64 mm Hg when discharge was rerouted from the spillway to the sluiceway. Most of the pressure increase was due to nitrogen and argon gas which accounted for a mean increase of 55 mm Hg; mean oxygen tension rose 9 mm Hg.

Although mean TGP levels changed, the difference between low and high values across the river at both Rkm 0.6 and 14.9 was similar, regardless of how water was released from Afterbay Dam (with the exceptions of the TGP measurment at 51.8 m on 18 August at Rkm 0.6, and TGP determined after the thunderstorm at Rkm 14.9 on 14 August). At Rkm 4.8, however, the cross river transect showed a considerably larger range of TGP on 19 August when water was passed through the sluicegates. Difference between low and high values increased from 22 to 55 mm Hg. Almost one-half of the increase may have been due to extending the transect an additional 6 m into slow moving water near the left bank. Even so, the range would have still increased to 40 mm Hg.

On 28 August, another cross-channel profile of gas pressures was measured at Rkm 0.6 (Table I6). At this time, both the spillway radial gates and the sluiceway were used to release the 62.1 m^3/c (2193 cfs) flow from Afterbay Reservoir. The mean hyperbaric pressure was lower and the range was less than seen in either of the previous profiles. The mean delta P was 79 mm Hg and ranged from 72-84 mm Hg (Table 16). The lack of a gradient across the river was unexpected; it was probably a result of the small sluicegate openings. Usually, TGP is reduced when sluicegates are open either a small or large amount and increased when opened to a mid-range. Maximum TGP measured on this transect was 38 mm Hg below the bubble growth threshold in the cardiovascular system, but 9 and 55 mm Hg greater than the environmental water and swim bladder thresholds, respectively. No other profiles were measured under this flow regime because of the lack of gradient in TGP at Rkm 0.6.

Table 16. Cross river transect of gas tensions at Rkm 0.6 on 28 August, 1987. (Q = 2193 cfs: range = 2145-2203 cfs; mean barometric pressure = 683 mm Hg, mean opening of sluiceway gates 1, 2, & 3 = 1.53, 1.40, & 1.36 ft, respectively; range = 1.14-1.53 ft, radial gates 1, 3,& 5 closed, and mean opening of radial gates 2 & 4 = 0.74 ft; range = 0.73-0.75 ft, weather = sunny with cooling and high thin cloud cover after 15:30).

Location[a] m(ft)	Time	Pressure (mm Hg)				Temperature (C)
		Total(^P)	O_2	N_2+Ar[b]	Water Vapor	
3.0(10)	15:08	756(72)	168	576	12.2	14.3
6.1(20)	15:18	758(74)	164	582	12.1	14.2
9.1(30)[c]	15:29	757(73)	167	578	12.1	14.2
12.2(40)	15:40	758(74)	168	578	12.2	14.3
15.2(50)	15:51	760(77)	167	581	12.2	14.3
18.3(60)	16:02	760(77)	162	586	12.2	14.3
21.3(70)	16:14	762(79)	162	588	12.3	14.4
24.4(80)	16:26	765(81)	165	588	12.2	14.3
27.4(90)	16:37	764(80)	168	584	12.1	14.2
30.5(100)	16:48	765(82)	169	584	12.2	14.3
33.5(110)	16:59	765(82)	170	583	12.1	14.2
36.6(120)	17:10	766(83)	169	585	12.2	14.3
39.6(130)	17:21	767(83)	166	589	12.3	14.4
42.7(140)	17:33	768(84)	165	591	12.3	14.4
45.7(150)	17:45	766(83)	163	591	12.1	14.2
48.8(160)	17:56	764(81)	162	590	12.1	14.2
51.8(170)	18:07	760(77)	161	587	12.4	14.5

a - distance from right bank when facing downstream.

b - nitrogen and argon pressures are calculated values.

c - in line with continuous monitoring probe.

Cross-channel gas distribution was markedly different at Rkm 0.6 on 4 September, 1986, when mean discharge was 17.08 m^3/s (603 cfs) greater, sluicegates were open about one-half way, all radial gates were open, and water temperature was higher. Mean delta P was nearly 104 mm Hg and a gradient of 40 mm Hg was noted.

These downriver and crossriver gas measurements illustrated that regardless of which single structure discharged water from Afterbay Dam, pressure gradients did not develop. Data collected in 1986, however, did demonstrate that under certain conditions, discharge from both the spillway and sluiceway may establish a gradient and reduce gas levels near the left bank, benefitting fish there. However, splitting the discharge may maximize production of hyperbaric pressures on the right bank. The last profile performed at Rkm 0.6 in 1987 showed that excessive gas production does not always occur when the sluiceway is in use. Attainment of these conditions should be possible at times even while operating under the constraints imposed by irrigation demand, power production, or recreational concerns.

Incidence of Gas Bubble Trauma

The incidence of gas bubble trauma (GBT) among brown trout in the upper monitoring section was higher at the beginning of 1987 than in either 1985 or 1986 (Table 17). Among all brown trout, the incidence rate remained between 30 and 45% until the end of July (Figure 32; Table 17); incidence rates for brown trout $\geq$ 356 mm followed the same general pattern and were substantially higher than for all brown trout except during

Table 17. Incidence of gas bubble trauma (GBT) in brown trout from Rkm 0-1.9 (section 1) of the Bighorn River during 1987 (data are from right bank unless noted otherwise).

Date	Time	All brown trout		Brown trout $\geq$ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/4	day	168	30	44	55
3/24	"	166	36	27	70
4/13 (Right bank)	"	177	40	27	70
4/14 (Left bank)	"	161	19	27	41
4/13&14 (Total-both banks)	"	338	30	54	56
4/27 (Right bank)	"	269	38	55	76
4/28 (Left bank)	"	184	19	21	52
4/27&28 (Total-both banks)	"	453	30	76	70
5/28	"	161	45	32	88
7/23	"	159	44	32	75
9/1	"	151	23	49	43
9/14 (Right bank)	night	179	6	63	5
9/15 (Left bank)	"	160	4	31	10
9/14&15 (Total-both banks)	"	339	5	94	6
9/28 (Right bank)	"	170	4	56	2
9/29 (Left bank)	"	185	1	42	0
9/28&29 (Total-both banks)	"	355	3	98	1
11/11	day	170	8	63	10
12/29	"	159	31	51	47

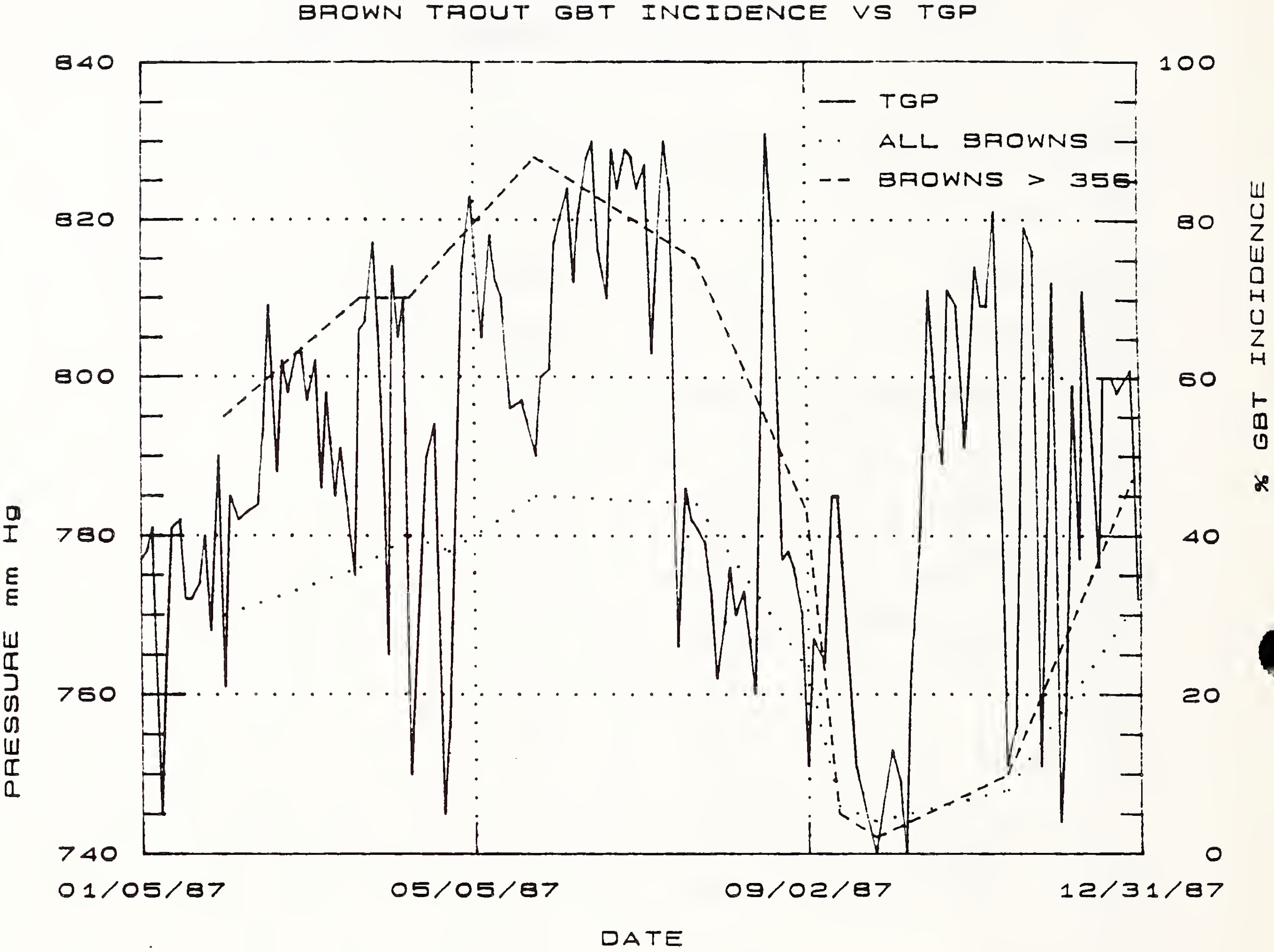


Figure 32. Incidence of GBT among brown trout along the right bank from Rkm 0-1.9 (Section 1) and TGP (Bouck gasometer data) at Rkm 0.6 during 1987.

September and November sampling. Sampling along the left bank of Section 1 during 1987 always showed lower incidence than along the right bank except for larger brown trout on 15 September. Peak brown trout incidence rates were observed on 28 May and were 45 and 88% for all browns and those ≥ 356 mm, respecitively. This corresponds closely to the time when peak levels were observed for brown trout in both 1985 and 1986 (White et al. 1986 and 1987). Incidence rates dropped to near zero in September 1987 and remained low until December when incidence rates for all browns increased to spring 1987 levels; incidence remained lower for the larger fish. Incidence rates for both brown and rainbow trout appeared to follow changes in TGP (Figures 32 and 33). From 14 September - 15 October, 1989, sluiceway gates in Afterbay Dam were operational and TGP and incidence remained low. During this period, minimum discharge ranging from 1736-2203 cfs (49.16-62.39 m^3/s) occurred and sluice gates 1, 2, and 3 had mean openings of 1.15, 1.14, and 1.00 ft, respectively. These small gate openings, combined with high water temperature (mean = 15.2°C) which decreased solubility, may help explain the low incidence rate.

Maximum GBT incidence in 1987 (88%) for larger brown trout was higher than any observed in 1985 or 1986. However, maximum incidence for all brown trout was intermediate between the 1985 and 1986 maximums. The average annual rate of incidence for all brown trout was 28.1%, which is identical to the 1986 rate and 17.5% greater than in 1985. The 1987 average incidence for browns ≥ 356 mm was 42.3%, which is higher than in 1986 (35.3%) or 1985 (15.4%).

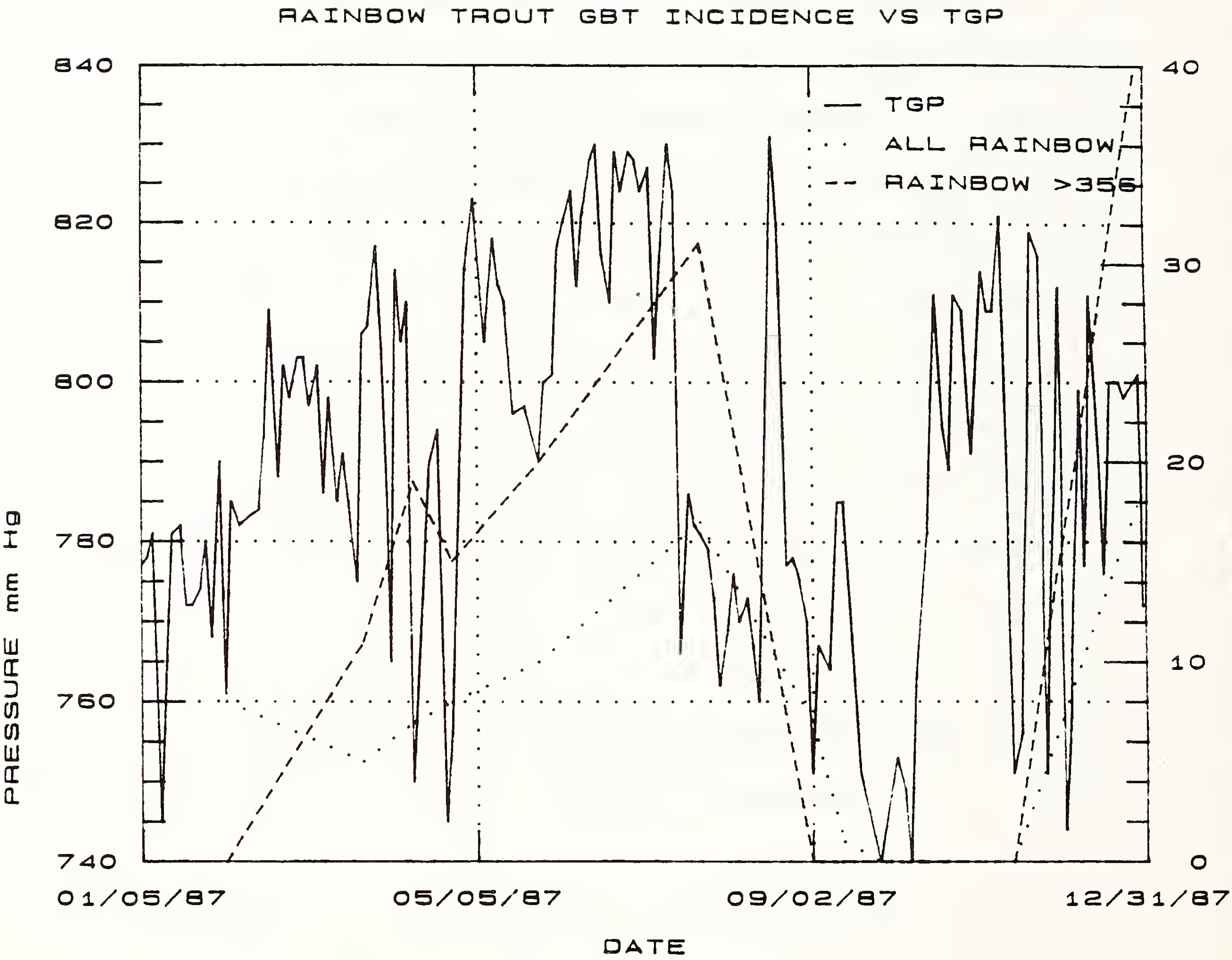


Figure 33. Incidence of GBT among rainbow trout along the right bank from Rkm 0-1.9 (Section 1) and TGP (Bouck gasometer data) at Rkm 0.6 during 1987.

Although GBT incidence rate for both size categories of brown trout reached maximum at the end of May, symptoms worsened as long as gas pressures remained high (Table 18). These total GBT ratings appear low because they include all brown trout captured in Section 1 on a specific date, even those with no visible GBT symptoms. If only brown trout with GBT were used, the rating for 28 May and 23 July would increase from 3.4 and 3.8 to 7.7 and 8.7, respectively. Mean total GBT ratings for brown trout along the left bank were 20-25% of those on the right bank for comparable periods of time except in mid-September when it equaled 44% of that on the right bank.

Condition factors of brown trout with visible GBT symptoms were always lower than for the total sample except on 29 September (Table 18). The higher condition factor for fish with GBT symptoms on 29 September may be biased since the mean value was calculated using only two fish. An interesting relationship between conditon factors and GBT incidence was observed during 1987 in Section 1; both peaked during the same period.

Table 18. Mean total GBT rating and condition factors for all brown trout captured during GBT incidence surveys in Section 1 (Rkm 0-1.9) of the Bighorn River during 1987.

Date	Mean total GBT rating	Mean K total sample	Mean K browns w/GBT
Right bank			
2/4	2.25	1.00	0.89
3/24	2.20	1.19	1.04
4/13	3.06	1.05	0.97
4/27	3.12	0.92	0.87
5/28	3.37	1.17	1.04
7/23	3.80	1.11	1.02
9/1	0.99	1.14	0.98
9/14	0.16	1.12	0.92
9/28	0.08	1.03	1.00
11/11	0.19	1.08	1.00
12/29	1.60	1.01	0.98
Left bank			
4/14	0.73	1.05	0.97
4/28	0.67	0.91	0.84
9/15	0.07	1.15	1.04
9/29	0.02	1.02	1.06

Additional analysis of condition factor data for all years may provide an explanation for this unexpected parallel of the two parameters.

On the right bank, a similar proportion of brown trout in each size category had minor GBT symptoms in 1986 and 1987.

Ninety percent of all brown trout and 83% of those $\geq$ 356 mm had minor symptoms (Table 19). Serious symptoms were noted in 7% of all browns and rose to 11% in the larger length group. Severe symptoms were found at higher levels than in 1986; 3% of all browns and 6% of the larger fish had severe external symptoms.

Peak GBT incidence among brown trout corresponded to a time when TGP was greater than the cardiovascular system threshold for bubble growth; the maximum for rainbow trout was observed just after TGP had dropped below the threshold (Figure 34). Fish without the benefit of hydrostatic pressure compensation were threatened by stasis of the blood and anoxia, primarily from late March to mid-July and intermittently from mid-October through the end of 1987. Gas bubble trauma incidence declined to near zero in September when TGP remained near the threshold level of bubble growth in environmental water. This threshold represents the pressure at which many external symptoms should begin to form. During other times of the year, incidence dropped or leveled off when gas pressures decreased to near this threshold. Although TGP occasionally dropped below the environmental water bubble formation threshold, it was always substantially higher than the swim bladder overinflation threshold. Swim bladder overinflation would probably not be a severe problem for most trout in the size groups sampled for incidence.

The threshold criteria discussed above applies to fish located at the water surface. Hydrostatic pressure, however, may be an important mitigating factor in preventing mortality since it compensates approximately 73.5 mm Hg hyperbaric pressure per meter of water (Figure 35). In Section 1 during 1987,

Table 19. Categorization of the severity of gas bubble trauma (GBT) in brown trout from Rkm 0-1.9 (section 1) of the Bighorn River during 1987. I = minor, II = serious and III = severe symptoms (MDFWP and MCFRU data).

Date	Time	All brown trout			Brown trout ≥ 356 mm		
		I	II	III	I	II	III
		No./%	No./%	No./%	No./%	No./%	No./%
2/4	day	43/84	4/8	4/8	18/75	2/8	4/17
3/24	"	55/92	3/5	2/3	16/84	2/11	1/5
4/13 (Right bank)	"	61/86	6/9	4/6	11/58	4/21	4/21
4/14 (Left bank)	"	29/94	2/7		10/91	1/9	
4/13&14 (Total-both banks)	"	90/88	8/8	4/4	21/70	5/17	4/13
4/27 (Right bank)	"	88/85	9/9	6/6	33/79	5/12	4/10
4/28 (Left bank)	"	31/91	3/9		10/91	1/9	
4/27&28 (Total-both banks)	"	119/87	12/9	6/4	43/81	6/11	4/8
5/28	"	63/88	9/13		21/75	7/25	
7/23	"	66/94	3/4	1/1	22/92	2/8	
9/1	"	34/97	1/3		20/95	1/5	
9/14 (Right bank)	night	11/100			3/100		
9/15 (Left bank)	"	7/100			3/100		
9/14&15 (Total-both banks)	"	18/100			6/100		
9/28 (Right bank)	"	7/100			1/100		
9/29 (Left bank)	"	2/100					
9/28&29 (Total-both banks)	night	9/100			1/100		

Table 19. (continued).

Date	Time	All brown trout I No./%	All brown trout II No./%	All brown trout III No./%	Brown trout ≥ 356 mm I No./%	Brown trout ≥ 356 mm II No./%	Brown trout ≥ 356 mm III No./%
11/11	day	14/100			6/100		
12/29	"	47/96	2/4		23/96	1/4	
1987 TOTAL (Right bank)		489/90	37/7	17/3	174/83	24/11	13/6

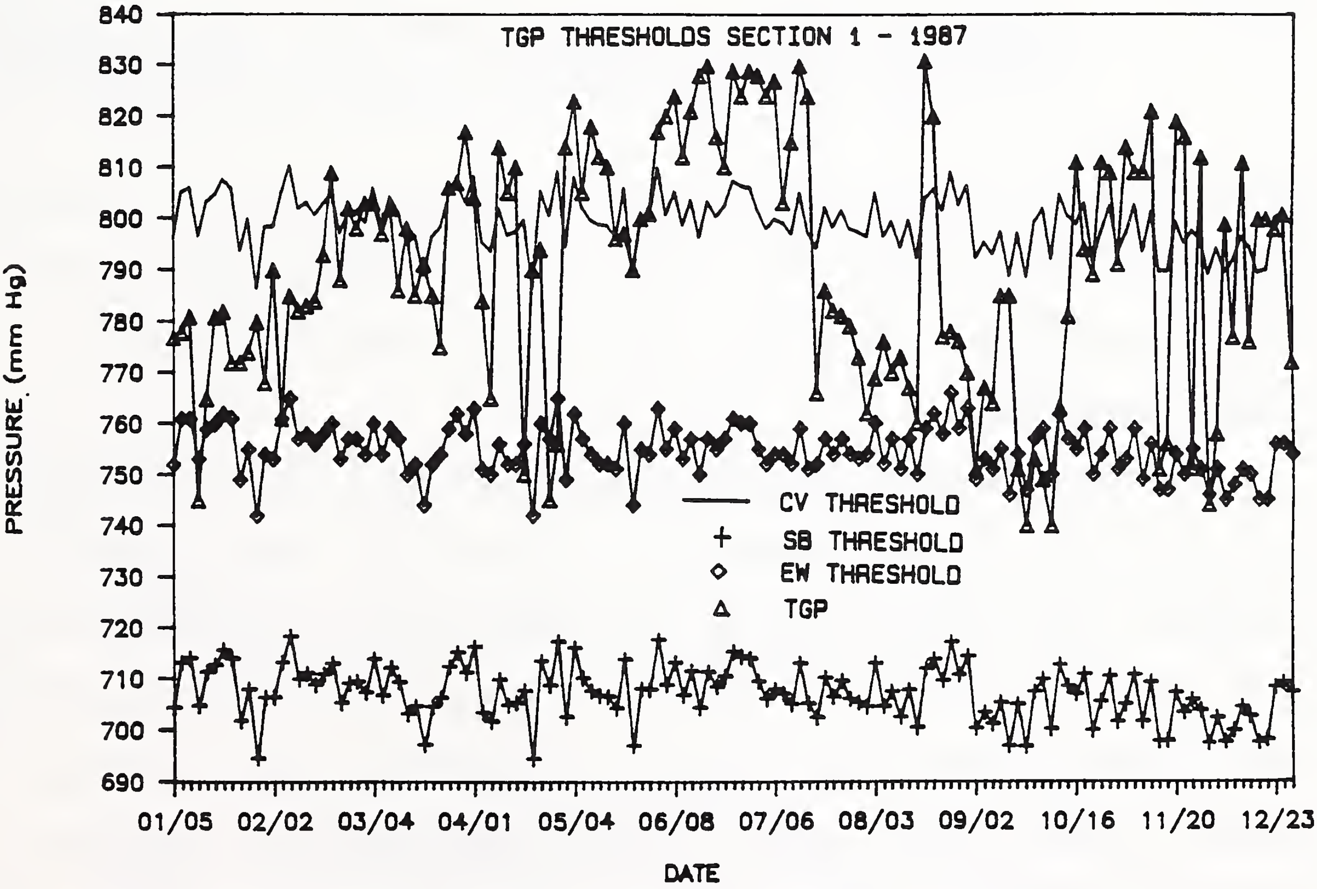


Figure 34. TGP (Bouck gasometer data) from Rkm 0.6 and threshold TGP for bubble formation in the cardiovascular system (CV), environmental water (EW), and swimbladder overinflation (SB) for for Section 1 in 1987.

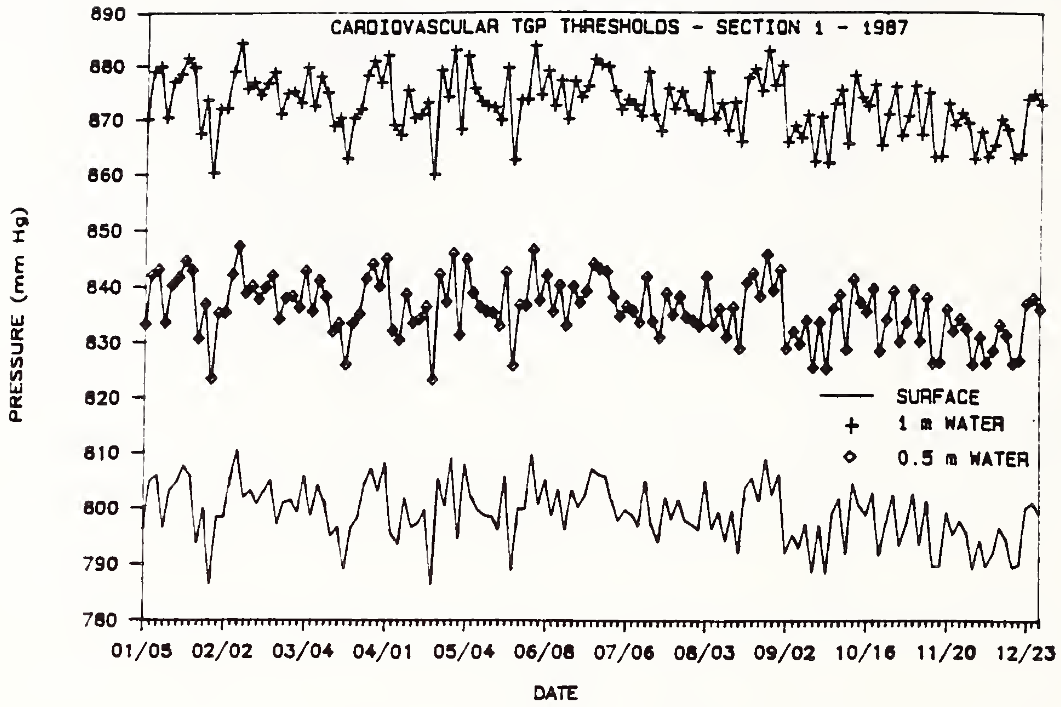


Figure 35. Threshold TGP for bubble formation in the cardiovascular system for trout in Section 1 at the water surface, 0.5 m, and 1.0 m below the surface during 1987.

cardiovascular bubble growth would not have occurred in fish that remained in 0.5 m water and trout at 1.0 m depth would not be subjected to bubble growth in gill lamella and formation of dermal emphysema.

In 1987, peak GBT incidence for rainbow trout in Section 1 occurred later and was lower than during 1986. The highest incidence rates during spring and summer 1987 were observed on 23 July when 17% of sampled rainbow trout and 31% of those ≥ 356 mm were affected (Table 20). However, incidence rates for both groups reached highest levels during sampling on 29 December; incidence seemed to follow the same general pattern as TGP (Figure 33). The lowest incidence rates were during a period of low TGP (-) extending from mid-September through mid-October.

Table 20. Incidence of gas bubble trauma (GBT) in rainbow trout from Rkm 0-1.9(section 1) of the Bighorn River during 1987 (data are from right bank unless noted otherwise).

Date	Time	All rainbow trout		Rainbow trout $\geq$ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/4	day	26	8	2	0
3/24	"	64	5	9	11
4/13&15 (Right bank)	"	126	7	42	19
4/14&16 (Left bank)	"	96	6	49	6
4/13-16 (Total - both banks)	"	222	7	91	12
4/27&29 (Right bank)	"	176	8	62	15
4/28&30 (Left bank)	"	100	8	40	20
4/27-30 (Total - both banks)	"	276	8	102	17
5/28	"	39	10	20	20
7/23	"	30	17	13	31
9/1	"	27	7	15	13
9/14&16 (Right bank)	night	89	1	39	0
9/15&17 (Left bank)	"	70	0	36	0
9/14-17 (Total - both banks)	"	159	1	75	0
9/28 (Right bank)	"	56	0	22	0
9/29 (Left bank)	"	61	0	18	0
9/30 (Both banks)	"	23	4	20	5
9/28-30 (Total - both banks)	night	140	1	60	2
11/11	day	29	0	7	0
12/29	"	22	18	10	40

Overall, 6.4% and 13.3% of all rainbows and those ≥ 356 mm, respectively, displayed external signs of GBT. This was intermediate between 1985 and 1986 incidence. Further investigation of differences in gas levels during these 3 years may provide an explanation for the 1987 rates for all rainbows being 7.3% lower and 2.2% higher than in 1986 and 1985, respectively. For larger rainbow, 1987 rates were 5.1% lower than those found in 1986 and 8.1% higher than in 1985. In contrast to previous years, all rainbow trout with GBT captured in 1987 had minor symptoms.

As in previous years, GBT incidence among brown trout was substantially lower (13-55%) in Section 2 than immediately below Afterbay Dam from February to early September (Tables 17 and 21). Peak incidence in Section 2 occurred later than in 1986 and later than in the upper section; the highest incidence observed was on 23 July when 23% and 48% of all browns and those ≥ 356 mm, respectively, had external GBT symptoms. Incidence among brown trout dropped to near zero by September and remained low through 1987 (Table 21). The annual average GBT incidence for 1987 in the middle section was 9.5% and 13.7% for all brown trout and those ≥ 356 mm, respectively. These are the highest rates we have observed for brown trout in Section 2.

As found upstream, GBT incidence among brown trout in Section 2 increased along with TGP, and both peaked simultaneously. The incidence rate for external symptoms increased more quickly after TGP rose above the cardiovascular system threshold level (Figure 36). The threshold for bubble

Table 21. Incidence of gas bubble trauma (GBT) in brown trout from Rkm 3.9-6.1 (section 2) on the Bighorn River during 1987 (data are from both banks unless noted otherwise).

Date	Time	All brown trout		Brown trout $\geq$ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/3	day	157	6	52	10
3/24	"	151	8	68	15
4/13 (Right bank)	"	84	23	38	34
4/14 (Left bank)	"	112	13	53	19
4/13&14 (Total - both banks)	"	196	17	91	25
4/27 (Right bank)	"	67	21	37	30
4/28 (Left bank)	"	110	13	60	18
4/27&28 (Total - both banks)	"	177	16	97	23
6/2	night	169	19	66	33
7/23 (Right bank)	"	180	23	71	48
9/1 (Right bank)	"	159	1	97	1
9/17 (Left bank)	"	160	0	101	0
9/28 (Right bank)	"	224	1	137	0
11/11	day	159	2	72	0

formation in the cardiovascular system is approximately equal to the environmental water threshold for fish 0.5 m below the water surface. If we used that water depth as an estimated average, TGP levels indicated dermal blisters could have formed on fish

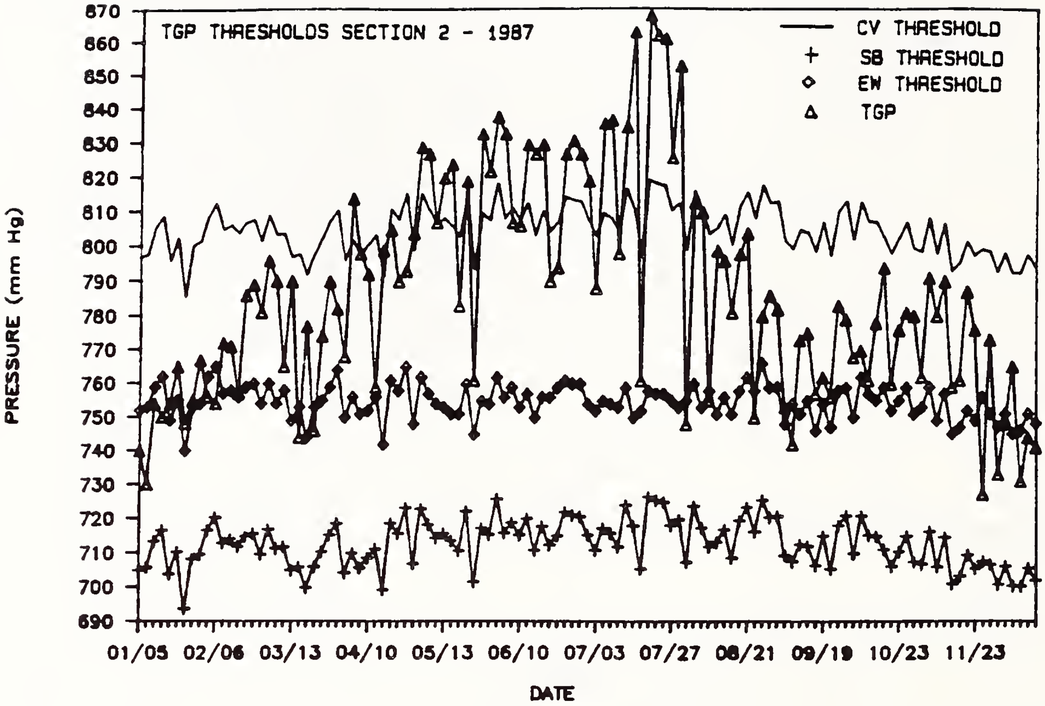


Figure 36. TGP (Bouck gasometer data) from Rkm 4.8 and threshold TGP for bubble formation in the cardiovascular system (CV), environmental water (EW), and swimbladder overinflation (SB) for for Section 2 in 1987.

primarily between early April and early August. Gas tensions fluctuated below that threshold level the rest of the year. Except for a short period in July during maximum TGP, a trout in 0.5 m of water in Section 2 would not have been subjected to vascular system bubble growth (Figure 37). Although we have not included graphs demonstrating the effect of a fish's position in the water column for environmental water and swim bladder overinflation, the same increase in threshold levels with increasing water depth would be observed. Only one fish, which represented <1% of the brown trout with GBT captured in 1987, had symptoms categorized as serious; all others displaying signs of GBT had minor symptoms (Table 22).

Although brown trout GBT incidence and TGP peaked

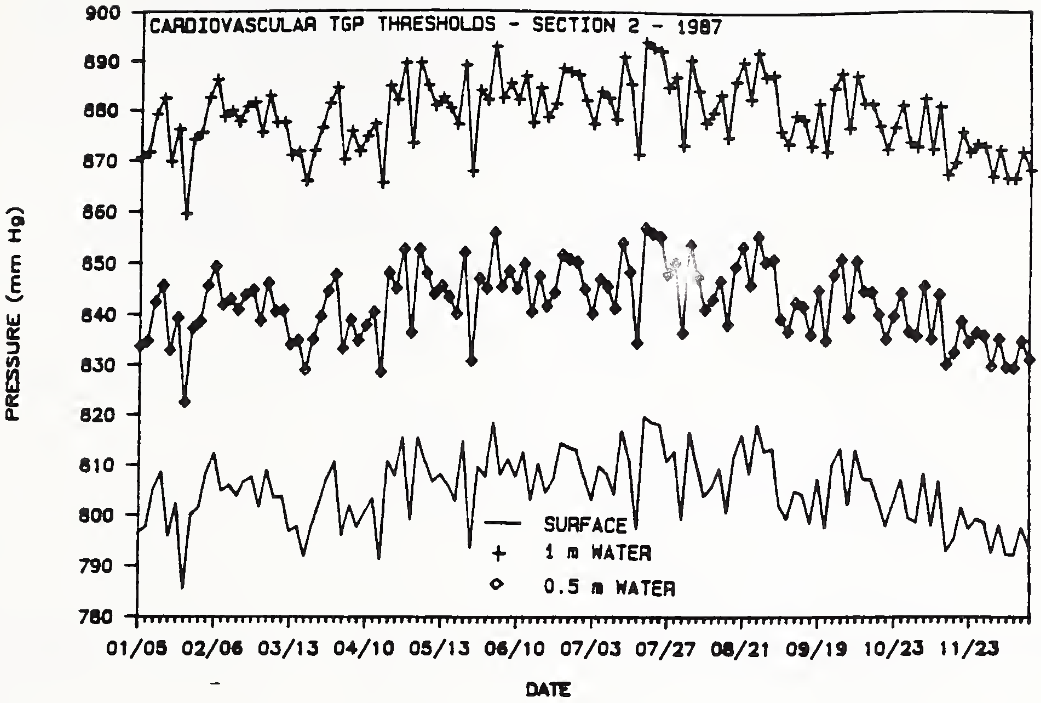


Figure 37. Threshold TGP for bubble formation in the cardiovascular system for trout in Section 2 at the water surface, 0.5 m, and 1.0 m below the surface during 1987.

simultaneously at Section 2 at the same time as TGP, incidence among rainbow trout peaked at 33% and 50% for all rainbows and those ≥ 356 mm, respectively, in early June, more than a month earlier (Table 23). These levels are much less than 1986 maximums but greater than those observed in 1985. This high incidence of rainbow trout GBT during late spring or early summer in Section 2 has always been greater than for brown trout during all 3 years of the study. The timing and higher incidence rate is probably related to use of shallow spawning areas, resulting in a greater vulnerability to GBT. No incidence occurred in either size group after the June sampling (Table 23). Average incidence rate in 1987 for all rainbow in Section 2 was 11.1% and 15.8% for rainbow trout ≥ 356 mm. As in the upper section in

Table 22. Categorization of the severity of gas bubble trauma (GBT) in brown trout from Rkm 3.9-6.1 (section 2) of the Bighorn River during 1987. I = minor, II = serious and III = severe symptoms (MDFWP and MCFRU data).

Date	Time	All brown trout			Brown trout $\geq$ 356 mm		
		I	II	III	I	II	III
		No./%	No./%	No./%	No./%	No./%	No./%
2/3	day	10/100			5/100		
3/24	"	12/100			10/100		
4/13 (Right bank)	"	19/100			13/100		
4/14 (Left bank)	"	14/100			10/100		
4/13&14 (Total-both banks)	"	33/100			23/100		
4/27 (Right bank)	"	14/100			11/100		
4/28 (Left bank)	"	14/100			11/100		
4/27&28 (Total-both banks)	"	28/100			22/100		
6/2 (Right bank)	night	32/100			22/100		
7/23 (Right bank)	"	40/98	1/2		33/97	1/3	
9/1	"	2/100			1/100		
9/17 (Left bank)	"	0/0			0/0		
9/28 (Right bank)	"	3/100			0/0		
11/11 (Right bank)	day	3/100			0/0		
1987 TOTAL		163/99	1/1		116/99	1/1	

Table 23. Incidence of gas bubble trauma (GBT) in rainbow trout from Rkm 3.9-6.1 (section 2) on the Bighorn River during 1987 (data are from both banks unless noted otherwise).

Date	Time	All rainbow trout		Rainbow trout $\geq$ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/3	day	18	11	6	33
3/24	"	14	0	8	0
4/13&15 (Right bank)		89	19	67	25
4/14&16 (Left bank)	"	20	5	10	0
4/13-16 (Total - both banks)	"	109	17	77	22
4/17 (Side channels)	"	86	5	75	5
4/27&29 (Right bank)	"	88	23	78	26
4/28&30 (Left bank)	"	68	10	52	14
4/27-30 (Total - both banks)	"	156	17	130	21
6/2 (Right bank)	night	12	33	8	50
7/23 (Right bank)	"	8	0	0	0
9/1 (Right bank)	"	6	0	2	0
9/17	"	32	0	13	0
9/18	"	14	0	4	0
9/17&18 (Total - both banks)	"	46	0	17	0
9/28	"	14	0	5	0
9/30	"	16	0	7	0
9/28&30 (Total - both banks)	"	30	0	12	0
11/11 (Right bank)	day	12	0	6	0

1987 and in contrast to previous years in Section 2, only minor symptoms of GBT were observed on rainbow trout.

As in 1986, incidence of GBT among brown trout in Section 3 (Rkm 12.2-15.4) was low throughout 1987 (Table 24). Incidence increased in April, June, and July with peak levels of 13% and 20% observed on 28 July; all other sampling dates showed virtually no GBT symptoms. Mean incidence rates for Section 3 were essentially identical to those in 1986. The 1987 incidence for all brown trout was 2.8% with incidences for those ≥ 356 mm being 4.7%. Only minor symptoms were observed on brown trout that had externally visible GBT (Table 25). As seen in the upper sections, peak GBT incidence among brown trout occurred at the same time as the highest TGP were observed. TGP reached maximum levels similar to those in Section 2 but much greater than those measured in Section 1. However, the time of exposure to TGP exceeding the threshold for bubble growth in the cardiovascular system decreased in a downstream direction. This helps explain the observed decrease in GBT incidence with distance downstream (Figure 38). Total gas pressure did not remain above or as far above the cardiovascular threshold at successive downstream sections, partly because of increased threshold levels caused by increasing oxygen partial pressures. Fish 0.5 m below the water surface in Section 3 would not be subjected to bubble formation in the blood during most periods in 1987; those that remained in 1.0 m water would never suffer from any form of GBT (Figure 39). The only time external symptoms of GBT were observed on rainbow trout in Section 3 was on 4 June (Table 26), which corresponded

Table 24. Incidence of gas bubble trauma (GBT) in brown trout from Rkm 12.2-15.4 (section 3) on the Bighorn River during 1987 (data are from both banks unless noted otherwise).

Date	Time	All brown trout		Brown trout $\geq$ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/5	day	165	1.2	94	1.1
3/25	"	163	0.6	101	1.0
4/15	"	213	4	85	8
6/4	"	151	7	82	12
7/28		167	13	99	20
9/3	"	151	0	100	0
9/15	"	207	0	117	0
9/30	"	144	0	78	0
11/12 (Right bank)	"	153	0	75	0

Table 25. Categorization of the severity of gas bubble trauma (GBT) in brown trout from Rkm 12.2-15.4 (section 3) of the Bighorn River during 1987. I = minor, II = serious and III = severe symptoms (MDFWP and MCFRU data).

		All brown trout			Brown trout ≥ 356 mm		
		I	II	III	I	II	III
Date	Time	No./%	No./%	No./%	No./%	No./%	No./%
2/5	day	2/100			1/100		
3/25	"	1/100			1/100		
4/15	"	8/100			7/100		
6/4 (Right Bank)	"	10/100			10/100		
7/28	"	22/100			20/100		
9/3	"	-			-		
9/15	"	-			-		
9/30	"	-			-		
11/12	"	-			-		
1987 TOTAL		43/100			39/100		

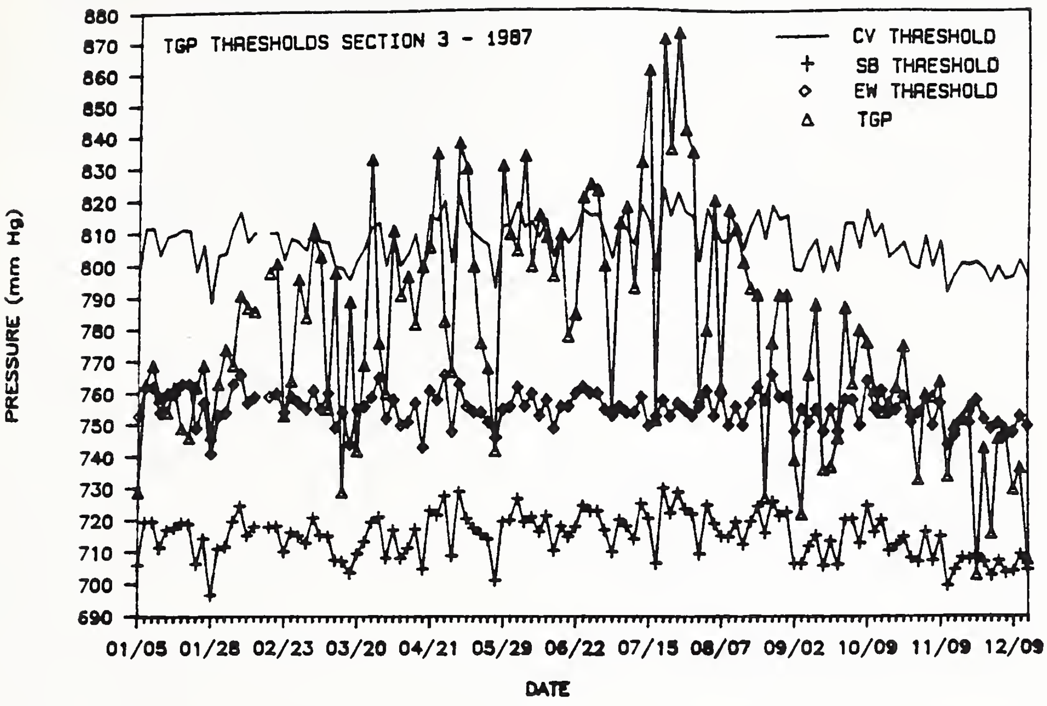


Figure 38. TGP (Bouck gasometer data) from Rkm 14.5 and threshold TGP for bubble formation in the cardiovascular system (CV), environmental water (EW), and swimbladder overinflation (SB) for for Section 3 in 1987.

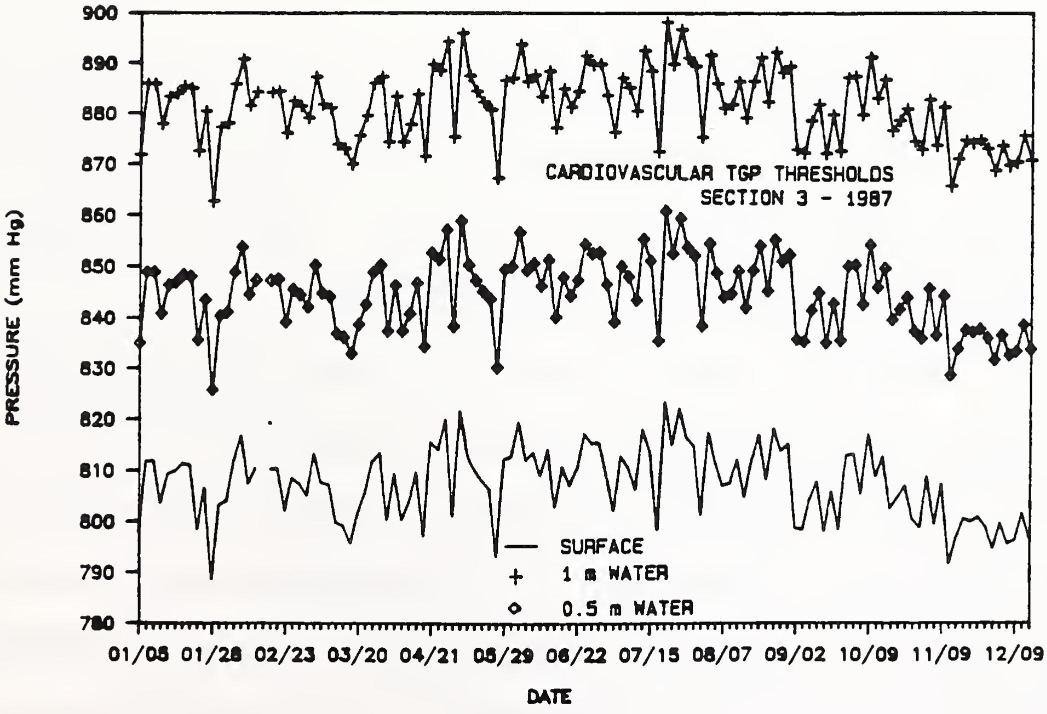


Figure 39. Threshold TGP for bubble formation in the cardiovascular system for trout in Section 3 at the water surface, 0.5 m, and 1.0 m below the surface during 1987.

Table 26. Incidence of gas bubble trauma (GBT) in rainbow trout from Rkm 12.2-15.4 (section 3) on the Bighorn River during 1987 (data is from both banks unless noted otherwise).

Date	Time	All rainbow trout		Rainbow trout ≥ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
2/5	day	34	0	9	0
3/25	"	36	0	12	0
4/15	"	72	0	21	0
6/4	"	23	13	12	25
7/28	"	20	0	9	0
9/3	"	22	0	17	0
9/15	"	47	0	37	0
9/30	"	39	0	24	0
11/12	"	27	0	18	0

to peak rainbow incidence in Section 2. The three rainbow trout captured on 4 June that displayed signs of GBT represented 13% of all the rainbow and 25% of those ≥ 356 mm. One had serious symptoms while the others had minor symptoms.

Mountain whitefish were collected in all three sections during incidence of occurrence sampling (Table 27). A total of 217 whitefish were captured in Section 1 during 1987, and 149 of these were ≥ 356 mm. In Section 2, 477 mountain whitefish of all sizes were captured, and 284 of these were ≥ 356 mm. We caught only 39 mountain whitefish in Section 3, 18 of which were ≥ 356 mm. No GBT was observed among the whitefish captured in Section 1 while one whitefish with minor symptoms was captured in both

Table 27. Incidence of gas bubble trauma (GBT) in mountain whitefish from the Bighorn River during 1987 (data are from right bank unless noted otherwise).

Date	Time	All mtn whitefish		Mtn whitefish ≥ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
		Rkm 0.0-3.9			
2/4	day	2	0	1	0
3/24	"	4	0	3	0
4/13&15 (Right bank)	"	11	0	6	0
4/14&16 (Left bank)	"	29	0	22	0
4/13-16 (Total - both banks)	"	40	0	28	0
4/27&29 (Right bank)	"	31	0	23	0
4/28&30 (Left bank)	"	41	0	31	0
4/27-30 (Total - both banks)	"	72	0	54	0
5/28	"	4	0	3	0
7/23	"	1	0	0	0
9/1	"	1	0	1	0
9/16 (Right bank)	night	17	0	10	0
9/15&17 (Left bank)	"	10	0	7	0
9/15-17 (Total - both banks)	"	27	0	17	0
9/28&30 (Right bank)	"	32	0	20	0
9/29 (Left bank)	"	23	0	15	0
9/28-30 (Total - both banks)	"	55	0	35	0
11/11	day	4	0	2	0
12/29	"	7	0	5	0

Table 27. (continued)

Date	Time	All mtn whitefish		Mtn whitefish ≥ 356 mm	
		No. caught	% w/GBT	No. caught	% w/GBT
			Rkm 3.9-6.1		
2/3 (Both banks)	day	12	8	8	13
3/24	"	18	0	14	0
4/13-17 (Total - both banks)	"	117	0	71	0
4/27-30 (Total - both banks)	"	133	0	87	0
6/2	night	13	0	10	0
7/23	"	21	0	14	0
9/1	"	21	0	13	0
9/17&18 (Total - both banks)	"	36	0	20	0
9/28&30 (Total - both banks)	"	76	0	38	0
11/11	day	30	0	9	0
			Rkm 12.2-15.4		
2/5	"	6	0	4	0
3/25	"	6	0	4	0
6/4	"	2	50	2	50
7/28	"	5	0	2	0
9/3	"	1	0	1	0
11/12	"	19	0	5	0

Sections 2 and 3 during 1987. The one fish with GBT caught in Section 3 on 4 June represented 50% of the sample for both size categories. The average annual incidence rate for mountain whitefish was never greater than 1% in the upper two sections and was 2.6% for all fish and 5.6% for those $\geq$ 356 mm in Section 3 during 1987. As in 1986, data suggest that mountain whitefish are less susceptible to gas supersaturation than trout. However, habitat use and behavior may minimize their exposure to excessive TGP or supersaturation may be limiting the population. Fickeisen and Montgomery (1975) found mountain whitefish to be less tolerant of gas supersaturation than any other species tested, including trout.

Population Estimates

Brown trout population estimates were obtained in two overlapping sections of the study area during April and September, 1987 (Tables 28 and 29). The spring estimate in the upper 6.1 Rkm (5414/km) was 52% larger than the estimate from the overlapping lower section (3559/km) (Rkm 3.9 - 15.4) monitored by MDFWP (Table 28). Compared to the lower section, both of the smaller size groups (140-290 mm and 291-429 mm) of brown trout were more abundant, with most of the increase due to more fish in the 291-429 mm length group. Although this size group was 98% more abundant in the upper reach, there were nearly 30% more brown trout/km larger than 430 mm in the lower section. These brown trout estimates were 93 and 58% larger in the upper and lower sections, respectively, compared to March 1986. Densities of brown trout in spring 1987 were higher in both of the smaller

Table 28. Brown trout, rainbow trout, and mountain whitefish population estimates from the Bighorn River below Afterbay Dam during April, 1987 (MCFRU and MDFWP data).

Section Rkm	Length interval (mm)	Number/km	80% Confidence intervals
		Brown trout	
0.0-6.1	140-290	1726	1406-2046
	291-429	3537	3082-3992
	430-620	151	116-186
	Total	5414	4857-5971
3.9-15.4	127-290	1582	1317-1847
	291-429	1782	1544-2020
	430-607	195	157-233
	Total	3559	3201-3917
		Rainbow trout	
0.0-15.4	89-188	519	339-699
	189-302	132	91-173
	303-480	186	154-218
	481-594	35	24-46
	Total	872	684-1060
		Mountain whitefish	
0.0-6.1	279-546	309	214-404

Table 29. Brown and rainbow trout population estimates from the Bighorn River below Afterbay Dam during September, 1987 (MCFRU and MDFWP data).

Section Rkm	Length interval (mm)	Number/km	80% Confidence intervals
		Brown trout	
0.0-6.1	216-302	1117	789-1445
	303-442	5282	4753-5811
	443-632	102	61-143
	Total	6501	5877-7125
3.9-15.4	191-302	1173	879-1467
	303-442	3739	3305-4173
	443-620	153	120-186
	Total	5065	4540-5590
		Rainbow trout	
0.0-15.4	216-315	173	103-243
	316-429	332	232-432
	430-480	63	46-109
	481-607	16	12-20
	Total	584	461-707

size groups than those found in spring 1986 throughout the upper 15.4 km but larger brown trout numbers decreased.

Spring 1987 rainbow trout population levels in the entire 15.4 km study reach were estimated at 872/km; for rainbow trout over 303 mm, numbers were slightly lower than the spring 1986 estimate. The rainbow trout estimate for the 89-188 mm size group is an underestimate since no attempt was made to capture these fish in the upper 6.1 km during electrofishing. Mountain whitefish numbers from the upper 6.1 km were slightly higher than the estimate obtained in March 1986 which included the entire upper 15.4 km.

Fall 1987 brown trout population estimates were larger than in spring 1987. Brown trout continued to be more abundant in the upper 6.1 km of the river, although differences were not as great as during spring. The upper section had an estimated 28% more brown trout/km than the lower section, Rkm 3.9-15.4 (Table 29). The higher population estimate in the upper section was due to 41% more fish in the middle size group (303-442 mm) and corresponded closely to the population structure observed during spring 1987. Estimates for the smallest size group in the two sections were essentially the same. Larger fish (443-632 mm) continued to be as much as 50% more numerous in the lower section than in the upper 6.1 Rkm. Total brown trout numbers for the upper 6.1 Rkm during September 1987 were 19% lower than estimated during fall 1986. However, the 1987 estimate did not include the 127-216 mm size range and this alone may be responsible for the decline. Total brown trout numbers in the lower section were approximately 15% greater than those from September 1986.

The fall rainbow trout population levels in the entire upper 15.4 Rkm were estimated at 584/km. This represents a 68% increase in the upper section and a 49% rise in the lower electrofishing section over levels in fall 1986. Insufficient numbers of mountain whitefish were captured to enable a population estimate.

Egg Incubation

Through the eyed stage, mean survival of brown trout embryos varied only 6.2% between sites in wedge boxes planted in November, 1986 (Table 30); highest survival was at Rkm 14.5. Variation between boxes at each site ranged from 1-3% except at Rkm 8.0 where one box had only 64.5% survival. Survival in the three other boxes at that site varied only 6.3%. Survival rates for brown trout embryos to the eyed stage in Porter boxes at Rkm 2.4 and 8.0 were similar (82.7 and 85.9%, respectively) but dropped to 57.0% at Rkm 14.5. Survival through hatching for brown trout embryos in wedge boxes was also high and followed the

Table 30. Brown trout egg survival from wedge and Porter boxes planted 20 November, 1986 at the early life history sites on the Bighorn River and in Afterbay Reservoir. Survival ranges are in parentheses.

River km	% survival to eyed stage		% survival through hatching	
	Wedge	Porter	Wedge	Porter
Afterbay	78.8 (78.0-79.4)	----	67.6 (53.5-77.9)	----
2.4	80.9 (80.5-81.5)	85.9	71.8 (57.6-80.2)	61.9
8.0	79.5 (64.5-89.0)	82.7	70.3 (66.7-73.2)	74.5
14.5	85.0 (84.0-87.0)	57.0	74.6 (72.6-77.3)	50.7

same pattern as seen for eyed eggs except levels were 9.1-11.2% lower. Variation in survival between boxes in Afterbay Reservoir and at Rkm 2.4 was much greater than through eye-up. Survival through hatching in the Porter boxes was highest at Rkm 8.0, where almost three-fourths of the fertilized eggs successfully hatched, and lowest at Rkm 14.5, where approximately half the eggs hatched. Two hundred thirty-five fry were not accounted for in the Porter box at Rkm 2.4. If these fry are assumed to have escaped, survival would increase to 80.3%, a rate higher than that observed at the other sites. Survival from eye-up through hatching in the Porter boxes remained high; at Rkm 2.4, survival was 75.8% while at both Rkm 8.0 and 14.5 survival it was over 90% (92.2 and 91.7%, respectively).

Gas levels during brown trout egg incubation were fairly low and similar to those found in previous brown trout egg incubation experiments (Table 31). Mean delta P's at Rkm 8.0 were almost identical to those found during 1985-86, those at Rkm 2.4 were lower and at Rkm 14.5 they were higher. Gas pressures were 7-16 mm Hg lower from fertilization to eye-up than from eye-up through hatching. Oxygen/nitrogen ratios calculated from the component levels of the hyperbaric pressure were substantially higher at Rkm 14.5 during 1987 compared to 1986.

Mean survival of rainbow trout embryos through the eyed stage in wedge boxes decreased downstream and varied from a low of 8.9% at Rkm 14.5 to 90.5% in the Afterbay (Table 32); variation between boxes was low at Rkm 14.5 (2.5%) and Afterbay (6.0%) but rose to 14.3 and 19.9% at Rkm 8.0 and 2.4,

Table 31. Mean and range of delta P's (mm Hg), the oxygen/nitrogen ratio, barometric pressure (mm Hg), and temperature (C) during brown trout egg incubation tests at three sites on the Bighorn River from November, 1986 - April, 1987. Oxygen/Nitrogen ratios in parentheses are calculated from oxygen and nitrogen partial pressures.

River	Eyed stage					Through hatching				
km	Dates	^P	O_2/N_2	B.P.	Temp.	Dates	^P	O_2/N_2	B.P.	Temp.
Afterbay	11/20-1/26					11/20-3/2				
2.4	11/20-1/22	86 (60-110)	0.16 (0.25)	682 (674-687)	6.4 (3.9-10.8)	11/20-3/18	93 (60-116)	0.19 (0.26)	681 (666-690)	4.7 (2.5-10.8)
8.0	11/20-1/27	76 (52-95)	0.46 (0.28)	682 (674-688)	6.2 (3.9-10.8)	11/20-3/17	85 (52-120)	0.51 (0.29)	682 (665-690)	5.1 (2.8-10.8)
14.5	11/20-1/27	70 (34-88)	1.09 (0.31)	683 (674-690)	6.2 (3.6-10.6)	11/20-4/6	86 (34-149)	0.98 (0.32)	682 (666-691)	5.4 (2.8-10.6)

Table 32. Rainbow trout embryo survival from wedge and Porter boxes planted 6 May, 1987 at the early life history sites on the Bighorn River and in Afterbay Reservoir. Survival ranges are in parentheses.

River	% survival to eyed stage		% survival through hatching	
km	Wedge	Porter	Wedge	Porter
Afterbay	90.5 (87.5-93.5)	----	0.3 (0.0-0.5)	----
2.4	38.5 (31.3-51.2)	49.3	15.6 (9.5-21.7)	44.1
8.0	37.3 (32.0-46.3)	46.5	20.5 (20.0-21.0)	42.1
14.5	8.9 (8.0-10.5)	42.4	2.5 ---	18.5

respectively. Low survival at Rkm 14.5 was probably related to mortality which began to manifest itself during egg planting and was probably not a direct result of environmental factors such as sedimentation or gas saturation levels; similar mortality was not apparent at the upstream sites.

Survival rates to the eyed stage in Porter boxes also decreased downstream but varied only 6.9% between Rkm 2.4 and 14.5. Survival through hatching for embryos in wedge boxes was highest at Rkm 8.0 (20.5%), dropped to 15.6% at Rkm 2.4 and was very low in Afterbay Reservoir and Rkm 14.5. These survival rates were substantially lower than through eye-up and those seen for brown trout last winter and spring. Variation in survival between boxes at each site was lower at hatching than at eye-up. Survival in the Porter boxes from fertilization to hatching was only 5.2 and 4.4% lower than survival to the eyed stage at Rkm 2.4 and 8.0, respectively, but at Rkm 14.5 it dropped 23.9%.

Mean hyperbaric pressure during this experiment was higher than during any other egg incubation test conducted to date (Table 33). Although delta P's were higher at all sites, oxygen/nitrogen ratios (^P-O_2/^P-N_2) were lower than those found during rainbow trout embryo incubation in 1985. Delta P's and oxygen/nitrogen ratios observed during previous brown trout egg tests were all lower than values measured from May - July, 1987. Mean gas pressures at each site were similar throughout the experiment; the delta P's during the fertilization to eye-up period were only 2-4 mm Hg lower than from eye-up to hatching.

Table 33. Mean and range of delta P's (mm Hg), the oxygen/nitrogen ratio, barometric pressure (mm Hg), and temperature (C) during rainbow trout egg incubation tests at three sites on the Bighorn River from May - July, 1987. Oxygen/Nitrogen ratios in parentheses are calculated from oxygen and nitrogen partial pressures.

River km	Eyed stage					Through hatching				
	Dates	^P	O_2/N_2	B.P.	Temp.	Dates	^P	O_2/N_2	B.P.	Temp.
Afterbay	5/6-6/25					5/6-8/8				
2.4	5/6-6/23	133 (96-153)	0.35 (0.28)	680 (670-688)	5.9 (4.7-6.9)	5/6-7/21	137 (92-154)	0.34 (0.28)	680 (670-688)	6.7 (4.7-10.0)
8.0	5/6-6/25	128 (95-153)	0.99 (0.34)	680 (670-687)	8.1 (5.8-9.4)	5/6-7/8	130 (95-153)	0.97 (0.34)	681 (670-687)	8.3 (5.8-9.7)
14.5	5/6-6/22	119 (71-153)	2.27 (0.39)	680 (671-687)	10.2 (7.2-12.2)	5/6-7/8	121 (71-153)	2.18 (0.39)	681 (671-687)	10.5 (7.2-12.2)

Oxygen/nitrogen ratios ($\text{^}P\text{-}O_2/\text{^}P\text{-}N_2$) were also constant with the largest decrease occurring at Rkm 14.5.

Survival data from 1986-87 and previous year's tests (White et al. 1986, White et al. 1987) for both brown and rainbow trout embryos to the eye-up or hatching stage did not suggest that TGP and nitrogen levels in the upper reaches of the study area increased mortality. This conclusion corresponds with that of other investigations that found no symptoms of GBT in eggs held under supersaturated conditions (Weitkamp and Katz 1980). This tolerance to elevated gas pressure is in part produced by hydrostatic pressure, which would be maximal in the substrate at the egg location as well as the internal pressure of the egg. Based on temperatures that would provide 73.5 mm Hg hydrostatic head/m (Colt 1984) and depths used by 85 rainbow trout in the

Bighorn River ($\bar{x}$ = 40.9±15.5 cm, range = 12.2-97.5 cm, Brian Sanborn, unpublished data), the mean compensation pressure for embryos in redds was 30 mm Hg, with a range from 9-72 mm Hg. Internal pressures of fertilized salmonid eggs vary from 15-40 mm Hg at 2-8 h after fertilization to 50-90 mm Hg near hatching (Alderice et al. 1984; Alderice and Jensen 1985). These portions of compensation pressure (P_{COMP}) could be as low as 24 mm Hg in a shallow water redd shortly after fertilization or as high as 162 mm Hg near hatching in a deep water redd. However, these factors would provide about 80-120 mm Hg of compensating pressure to the embryo in an everage redd. This would lower the maximum uncompensated delta P observed during rainbow embryo incubation during 1987 to 34-70 mm Hg, or under 110% TGP. After hatching occurs, these components of compensation pressure would be lost. Nebeker et al. (1978) provided supporting evidence of this, finding that steelhead trout eggs, embryos, and newly hatched fry prior to swim-up were more resistant to supersaturated water than swim-up fry and later stages.

Brown Trout Fry Survival Tests

Subsamples of brown trout fry reared at the early life history study sites were moved upstream to the gagehouse (Rkm 0.6). Also, one-half of the control fry reared in non-supersaturated water in Afterbay Reservoir were moved to Rkm 0.6. Over a 29 d period, TGP at Rkm 0.6 was 6-53 mm Hg higher than the bubble formation threshold for environmental water; the mean difference was about 30 mm Hg (Figure 40).

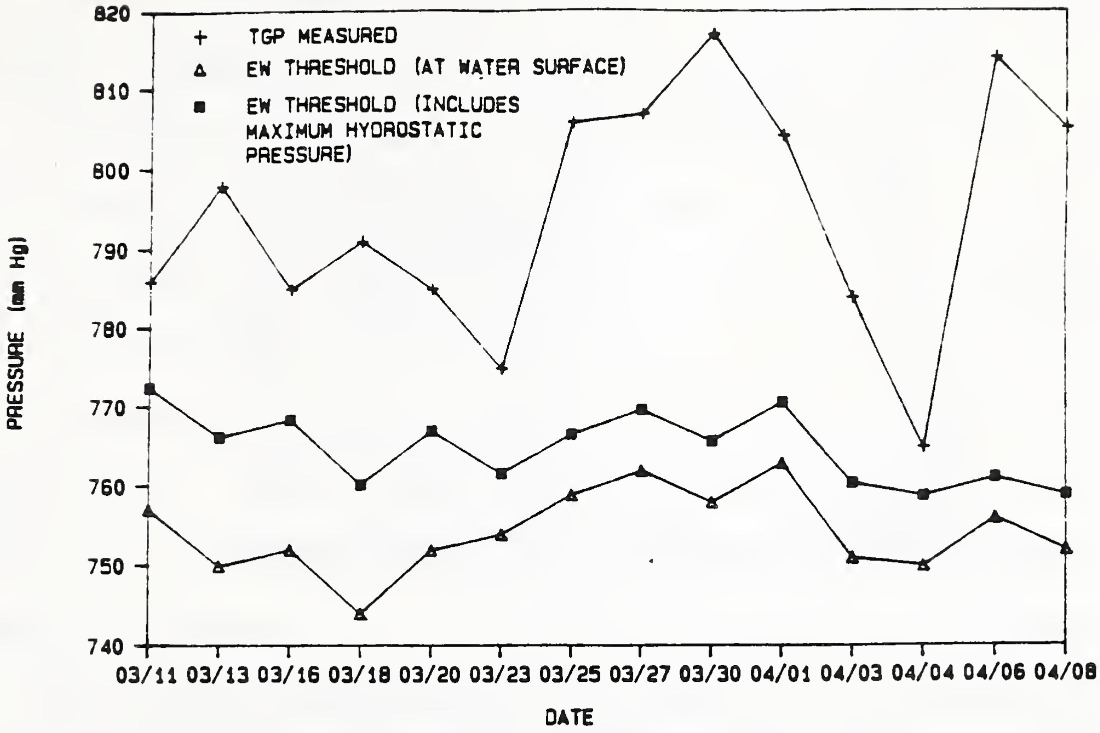


Figure 40. Total gas pressure and the threshold TGP for bubble growth in environmental water determined from Bouck gasometer data at the gagehouse (Rkm 0.6), Bighorn River, 11 March - 8 April, 1987.

Control fry were expected to be highly susceptable to bubble growth in the buccal and peritoneal cavities which may result in mortality. Although TGP remained much higher than the environmental water threshold, fry survival was high. Only seven (4.1%) of 171 brown trout fry died. Four of these died when TGP peaked on 30 March. This was one of two times when TGP exceeded the cardiovascular system threshold. Gas emboli were visible on five of the seven mortalities. Monitoring of control fry moved to Rkm 0.6 continued through much of 1987. Analysis of the physical factors fry were exposed to through time will enable us to define the general range of threshold levels for brown and rainbow trout in the fry stages.

Recently emerged brown trout fry incubated at Rkm 2.4 were held at the gagehouse from 23 March - 11 June, 1987. Mortality remained relatively low until day 51 and peaked on day 72 (Figure 41). Dead fry were included in mortality data only if GBT symptoms were visible. Cumulative mortality rose to 36.2% by the end of the bioassay. One hundred fifty-nine bubbles were observed on the 133 dead fry. Bubbles along the ventral surface in the peritoneal cavity were most common (58%). Thirty percent of the bubbles were located in the buccal cavity, 11% in the eyes, producing exophthalmia, and 1% on the external surface. Mean size of dead fry during the 80 d bioassay was 24 mm. The corrected mean daily TGP measured by the continuously recording Common Sensing tensionometer was minimum (738 mm Hg) on day 33 and peaked on days 42 and 73 at 825 and 828 mm Hg, respectively (Figures 41 and 42). The maximum TGP reading observed on days 71, 72, and 73 was 822, 820, and 836 mm Hg, respectively. Oxygen pressure was lower on day 72 than earlier tin the bioassay but remained higher than measured at the beginning of the experiment (Figure 43). Water temperature increased throughout the bioassay (Figure 44). Changes in mean daily barometric pressure corresponded closely to bubble threshold levels and averaged 682 mm Hg (670-694 mm Hg) during the test. Total gas pressure was always greater than the threshold for swim bladder overinflation (Figure 42) and except for two short periods of time during the first half of the bioassay, TGP was also greater than the threshold for bubble growth in environmental water.

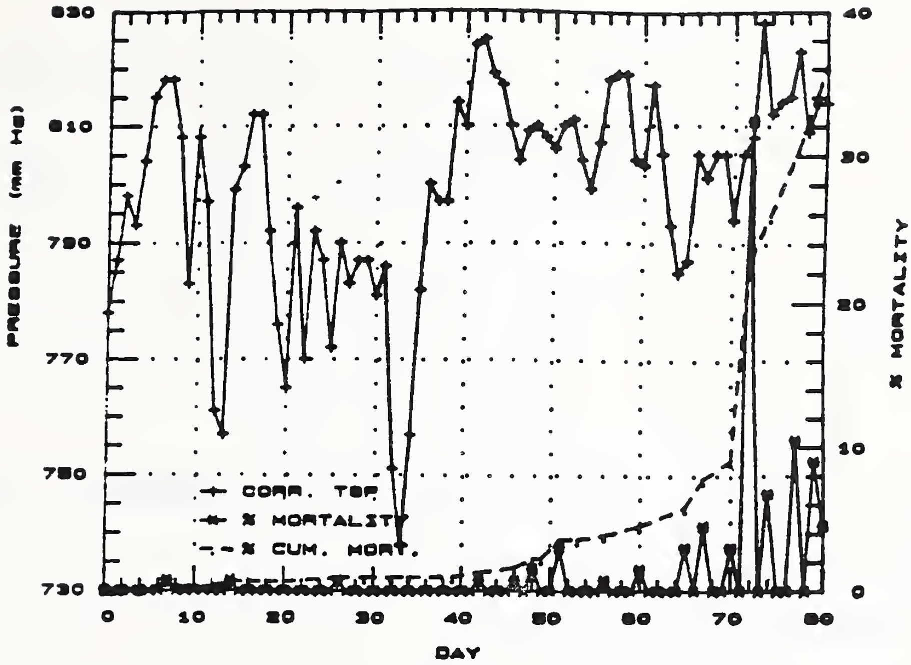


Figure 41. Corrected TGP, percent mortality, and cumulative mortality for brown trout fry hatched at Rkm 2.4 and held at Rkm 0.6, 23 March - 11 June, 1987. Total number of fish at beginning of bioassay = 309.

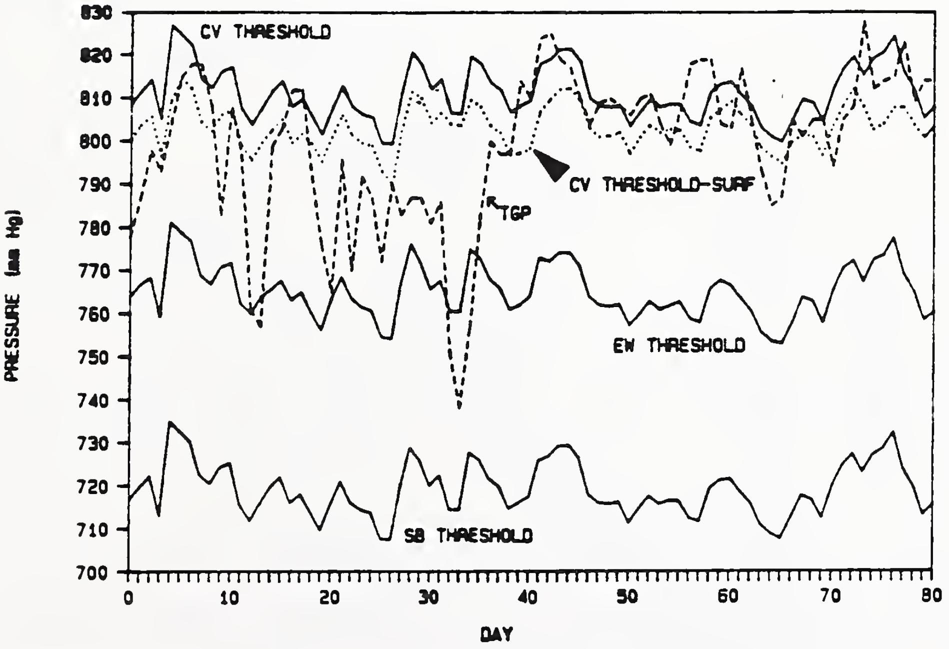


Figure 42. Mean daily TGP measured by the Common Sensing tensionometer, and the maximum threshold TGP for bubble formation in the buccal cavity, swim bladder, and vascular system as well as the cardiovascular threshold at the water surface at Rkm 0.6, 23 March - 11 June, 1987.

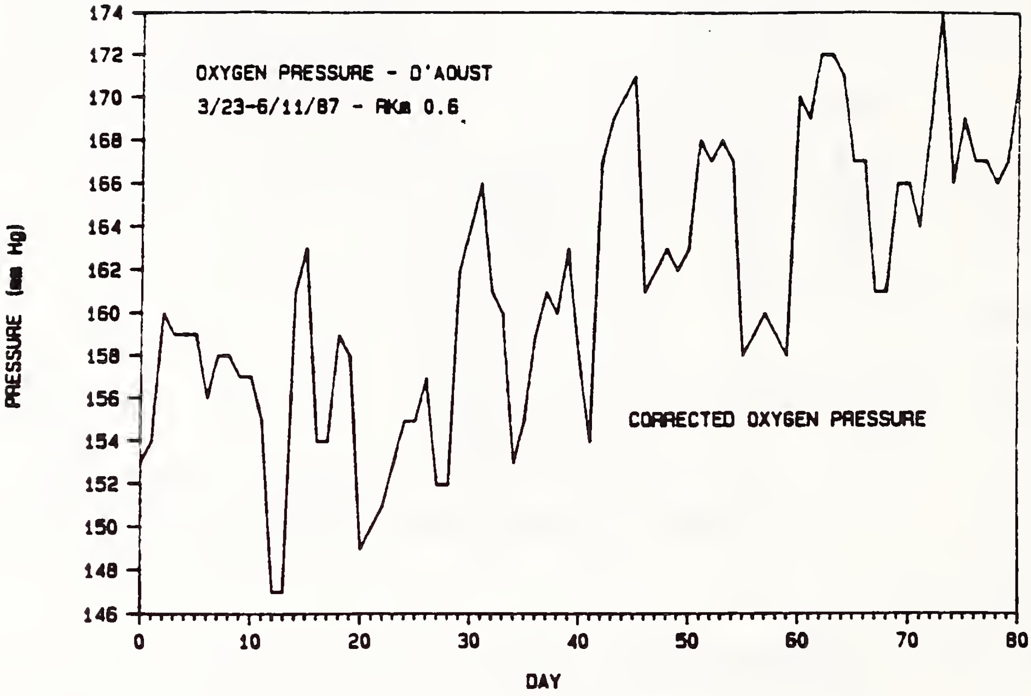


Figure 43. Corrected mean daily oxygen pressure at Rkm 0.6 measured by the Common Sensing tensionometer, 23 March - 11 June, 1987.

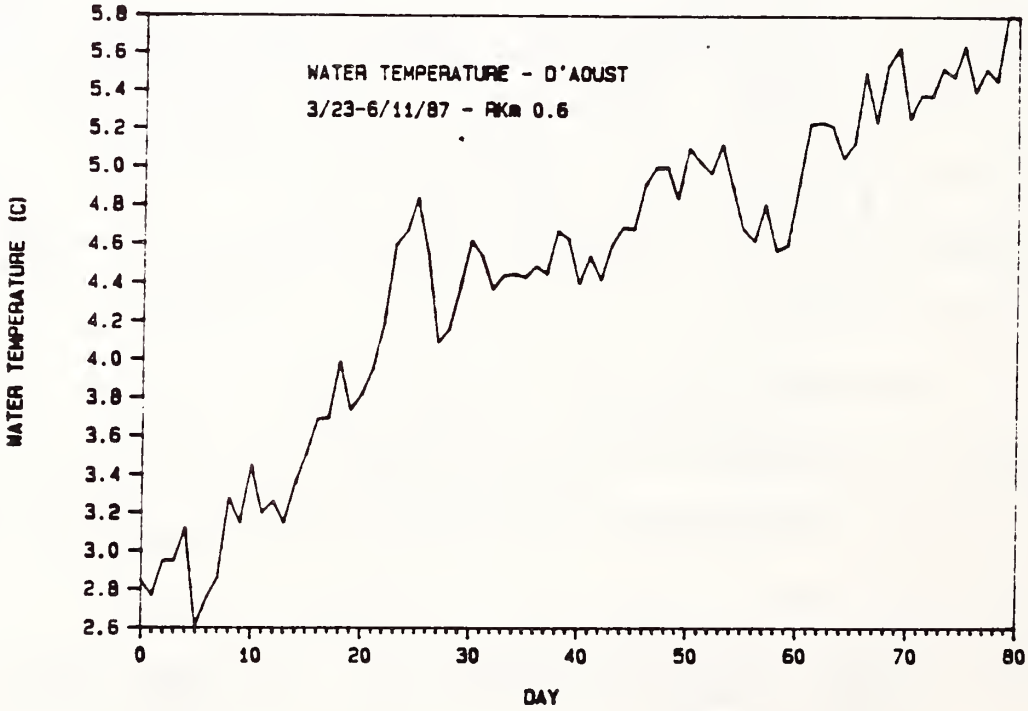


Figure 44. Mean daily water temperature (C) measured by the Common Sensing tensionometer at Rkm 0.6, 23 March - 11 June, 1987.

During the first 38 d of the bioassay, TGP fluctuated but tended to remain below the cardiovascular threshold levels, even at maximum water depth. As would be expected, very low mortality occurred. One of the three fry that died during this period had a present in the peritoneal cavity while the other two had buccal bubbles.

During the second half of the bioassay, TGP was usually equal to or greater than the cardiovascular - water surface threshold and fluctuated above and below the cardiovascular system threshold at maximum available depth. This increase in TGP apparently was sufficient to increase mortality at approximately day 50; mortality remained elevated through the end of the experiment.

A general relationship between fry mortality and TGP was apparent during the last half of the bioassay. Once TGP reached and maintained levels approximately equal to the cardiovascular system threshold, mortality rate increased. High water hardness and pH, as well as a potentially higher resistance of fish, may affect the threshold level for fish in the Bighorn River. Also, since a large portion of mortality appeared to be a result of starvation or excessive energy expenditure caused by buccal or peritoneal cavity bubble growth, a considerable time lag between bubble development and actual mortality occurred. This would further mask the relationship between mortality and TGP. Analysis of the other brown and rainbow trout fry bioassays conducted at the gagehouse and at each early life history site should allow identification of the maximum TGP level that will not affect recruitment.

Examination of live brown trout fry held during May and June, 1987 showed substantial numbers maintaining abnormal swimming positions due to the presence of bubbles (Table 34). Overall, 31.6% of the brown trout fry held at Rkm 0.6 in late May had to compensate for excessive buoyancy; this increased to 49.7% on 11 June. Further downstream, the percentage of fish with buoyancy problems varied from 41.9-45.9% during June, except for one occasion at Rkm 14.5 when almost no affected fish were observed. In a natural situation, fish with similar equilibrium problems would have greatly reduced chances for long-term survival. If these values are representative of proportions of fry affected in the Bighorn River, elevated TGP may be the most important single factor affecting fry survival.

Catchability Study

On 13 June, 1987, a catchability study was conducted to determine if fish with GBT made up a smaller percentage of the catch than their proportion in the population. If so it would suggest that gas supersaturation was effectively removing a portion of the population from the sport fishery. Through the assistance of approximately 24 volunteer anglers, 59 trout were caught, 45 brown trout and 14 rainbow trout. Anglers fished on the right bank between Afterbay Dam and Rkm 1.9 (RM 1.2) with most effort between Rkm 0.8 and 1.2 (RM 0.5-0.75).

Approximately 78 and 93% of all brown trout caught and those

Table 34. Proportions of live brown trout fry with obvious buoyancy problems which affected swimming ability during May and June, 1987 on the Bighorn River.

Location Rkm	Date	% of fry with buoyancy problem	Total no. of fish
0.6 (control fish)	5/29	30.6	124
0.6 (Rkm 2.4 fish)	5/29	29.7	269
0.6 (Rkm 8.0 fish)	5/30	32.3	223
0.6 (Rkm 14.5 fish)	5/30	33.3	261
0.6 Total		31.6	877
0.6 (Rkm 2.4 fish)	6/11	56.2	169
0.6 (Rkm 8.0 fish)	6/11	42.4	151
0.6 Total		49.7	320
2.4	6/12	45.9	632
8.0	6/11	44.1	793
14.5	6/16	0.5	200
14.5	6/23	41.9	62

over 356 mm (14 in), respectively, had external GBT symptoms. Eighty-three percent of all brown trout caught had minor symptoms of GBT, 14% had serious symptoms, and 3% had severe symptoms. Sixty-one percent of the larger brown trout had minor symptoms, 31% serious symptoms, and about 8% had severe symptoms, substantially reducing the chances for long-term survival. Rainbow trout showed a much lower GBT incidence rate - 21% for all rainbow trout and 29% for fish 356 mm (14 in) or greater; also, only minor symptoms were observed. Seventy-nine percent of the rainbow trout caught were of hatchery origin.

On the evening of 14 June, 1987 the same river reach was electrofished. From Rkm 0.0-1.2 (RM 0.00-0.75), GBT incidence among all brown trout was 50%, and for brown trout 356 mm (14 in) or greater, it was 56%. Rainbow trout had an overall GBT incidence rate of 9%, while for larger rainbow trout the rate was 17%. These incidence rates are substantially lower than data obtained by angling. Since more than 96% of the brown trout and 100% of the rainbow trout caught by anglers were between Rkm 0.8-1.2 (RM 0.5-0.75), we electrofished this area to see if incidence was higher than in other reaches. Of the 122 brown trout and 21 rainbow trout captured, GBT incidence for brown trout was 65% in both categories, and 10% for all rainbow trout; rainbow trout over 356 mm (14 in) had a 15% incidence rate. Most brown trout had minor symptoms, 77% for all brown trout and 65% for fish 356 mm (14 in) or larger, while serious symptoms were present on 22 and 29% of all brown trout and the larger brown trout, respectively. Severe symptoms were displayed by 1% of all brown trout and 6% of the larger brown trout. As with the angler caught rainbow trout, only minor symptoms were observed among the rainbow captured during electrofishing.

Although the incidence of GBT was higher from Rkm 0.8-1.2 (RM 0.5-0.75) than in the entire stretch that was electrofished, it was still lower than the incidence rate determined from angling. This suggests that minor symptoms of GBT do not remove brown and rainbow trout from the fishable population. However, most trout severely affected by GBT are probably unavailable to anglers. The catchability study also demonstrated that, as seen in the past by others, the proportion of the population affected and the severity of symptoms among brown trout was greater than for rainbow trout.

Afterbay Operation Monitorings

Uncorrected mean daily delta P measured by the Common Sensing tensionometer at Rkm 0.6 seemed to follow changes in the opening (flow) of sluiceway gate 1 during much of 1987 (Figure 45). As observed in previous years, the other two sluiceway gates were operated in a pattern essentially identical to sluice gate 1. When mean daily delta P reached elevated levels of 120 mm Hg and above, the daily mean sluicegate openings varied from 1.75-3.5 ft, and the mean opening was 2.44 ±0.52 ft. Delta P levels of this magnitude would allow TGP's to rise above the 1987 mean cardiovascular system threshold level of 799 mm Hg at Rkm 0.6. However, both larger and smaller sluicegate openings appeared to coincide with lower hyperbaric pressures. The mean opening of sluicegate 1 was 1.42 ±0.84 ft for mean daily delta P levels less than 120 mm Hg. As would be expected, the range of openings for the lower gas pressures was larger, varying from 0-5.1 ft compared to 0.91-3.87 ft for those above the mean cardiovascular system threshold. Although minimizing sluiceway gate openings in the mid-range would not eliminate TGP's above cardiovascular threshold levels, it could reduce a fish's long-term exposure and may be feasible during parts of the year.

Mean daily openings of the spillway radial gates did not correspond with gas levels or sluicegate openings (Figure 46).

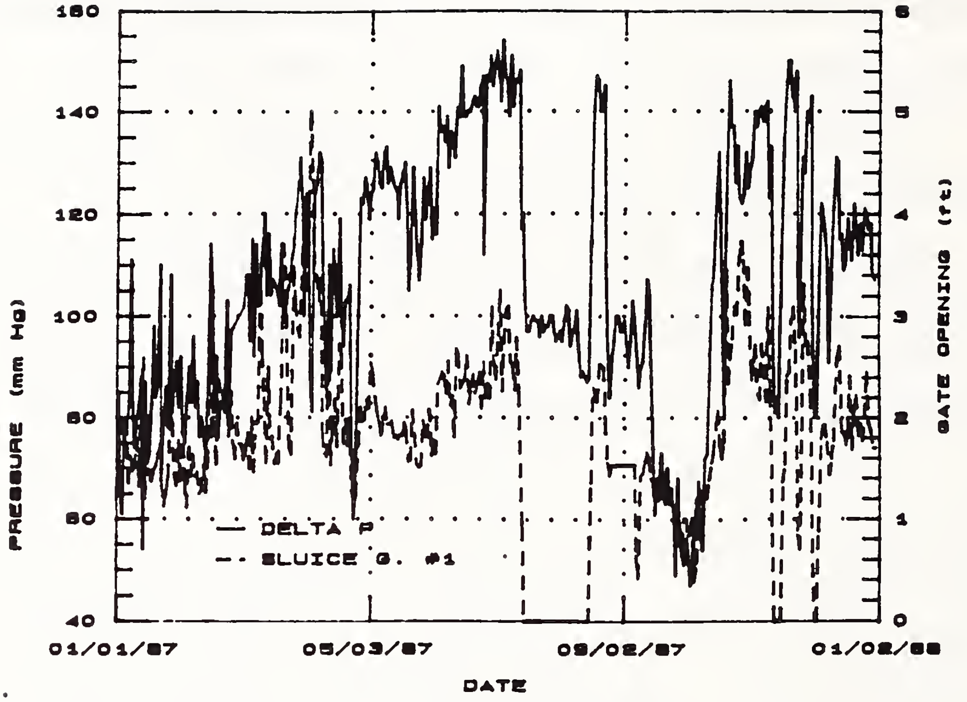


Figure 45. Uncorrected mean daily delta P on the right bank at Rkm 0.6 and the mean opening of sluiceway gate number one during 1987.

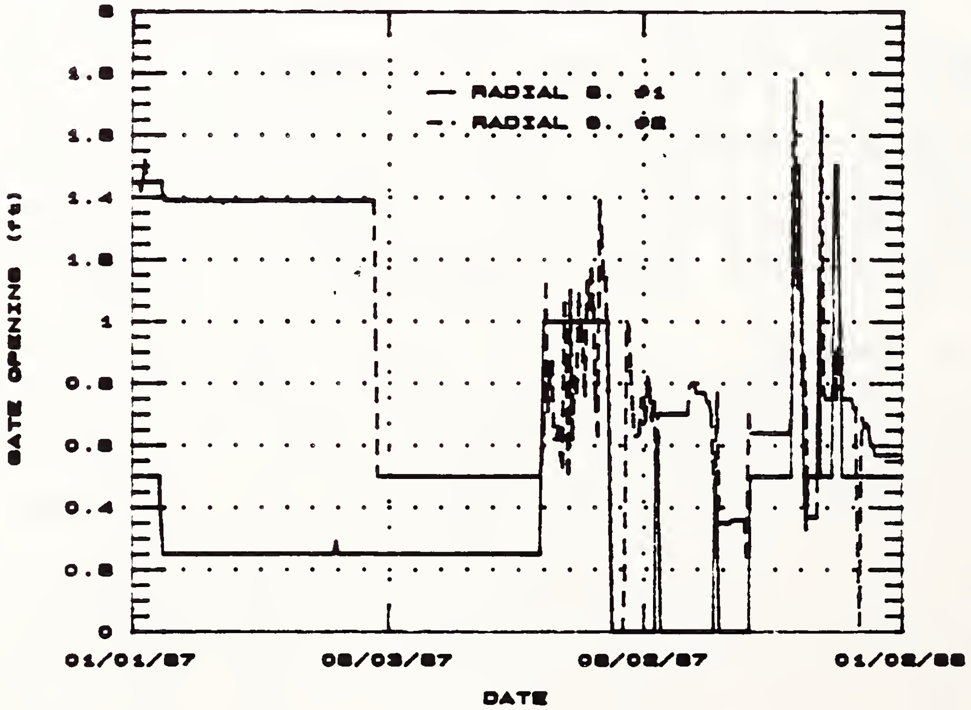


Figure 46. Mean daily opening of spillway radial gate numbers 1 and 2 on Afterbay Dam during 1987.

The opening of radial gate 1 is representative of radial gates 3 and 5, while radial gates 2 and 4 were opened to the same height. Since the sluiceway was not in use, radial gates 2 and 4 were used to maintain a uniform river discharge, from 16 July - 16 August which resulted in the large fluctuation in openings of these gates. Radial gates were usually opened to a specific height and maintained there for a long period of time. Even though the gates remained open the same amount, fluctuations in Afterbay Reservoir elevations altered discharge from them. Discharge through the radial gates is not possible when the Afterbay Reservoir elevation drops below the spillway elevation of 3179.5 ft (969.11 m). Mean daily Afterbay elevations rarely drop below this level (Figure 47). However, the elevational change in Afterbay Reservoir can be much greater than the mean values suggest (Figure 48); the average variation in daily Afterbay levels during the second half of 1987 was 5.76 ft, but changed as little as 0.79 ft and as much as 15.145 ft. During periods of large fluctuations, the minimum elevation often dropped below the spillway crest. Early July and from mid-October through the end of the year were periods of low minimum elevations (Figure 49); levels dropped below the spillway crest on 22 days. Closure of the sluicegates for repairs from 16 July - 16 August probably prevented lower minimum levels in Afterbay Reservoir during that time since all discharge passed through the radial gates.

Since the function of Afterbay Dam is to reregulate discharge in the river below Yellowtail Dam, daily reservoir

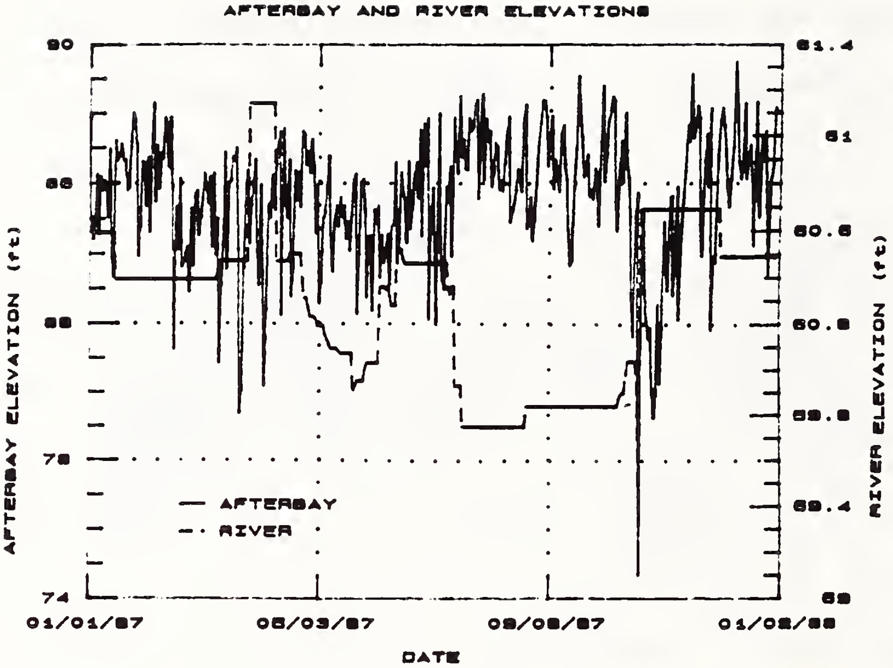


Figure 47. Mean daily elevations of Afterbay Reservoir and the Bighorn River at Rkm 0.6 during 1987.

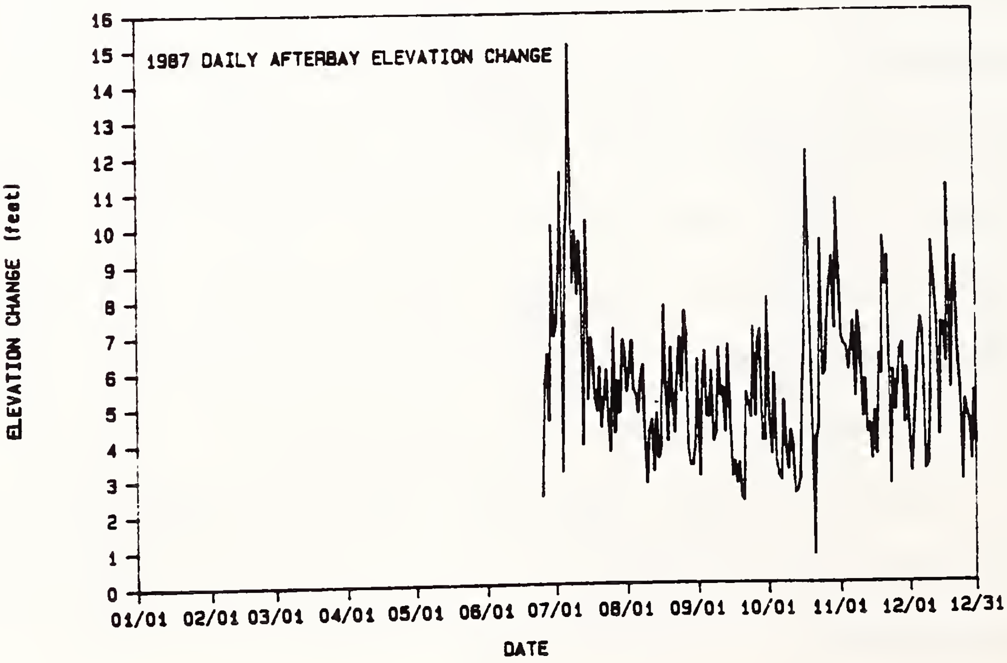


Figure 48. Daily fluctuations in Afterbay Reservoir elevations measured by the Hydromet system during 1987.

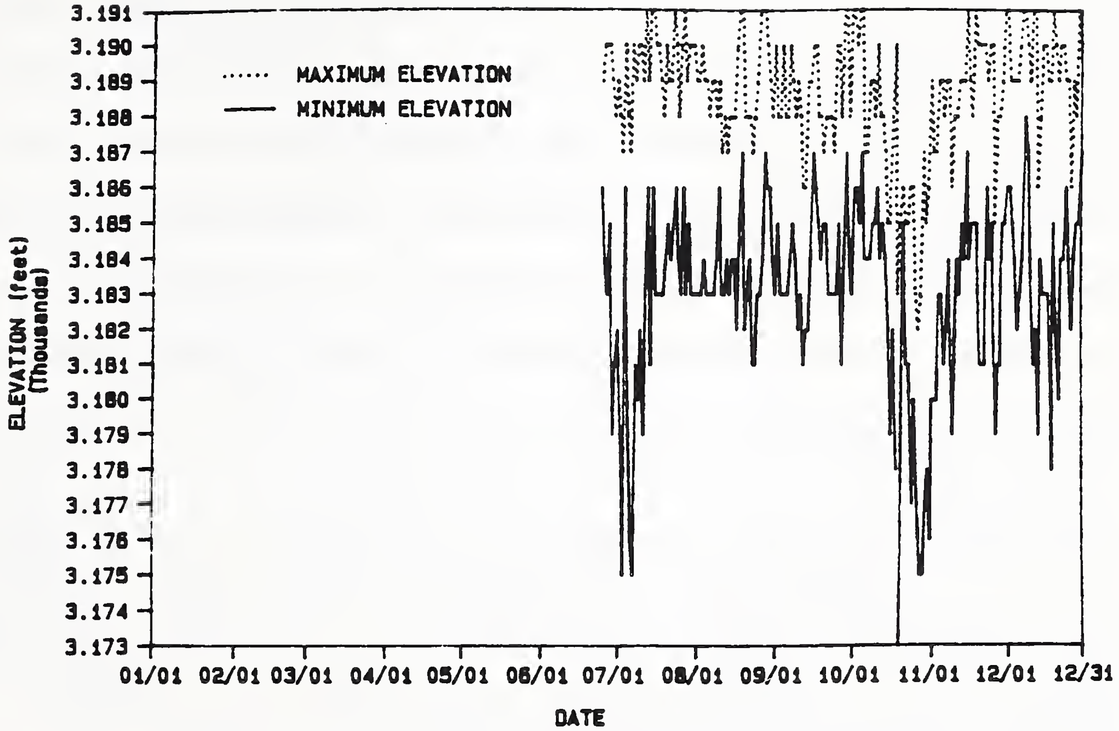


Figure 49. Daily maximum and minimum Afterbay Reservoir elevations measured by the Hydromet system during 1987.

fluctuations and associated changes in sluicegate openings are part of the usual operating procedure. Avoiding use of the sluicegate mid-range openings is impossible, but if the percentage of total discharge passed through the sluicegates is varied, TGP would be reduced in many cases. Drawbacks to this may include increased duties for the control room operator, additional wear on the sluicegates, and less flexibility for sluicegates to respond to changes in the river stage height. The feasibility of increasing storage in Afterbay Reservoir, construction of a bypass penstock without electrical generation facilities, or placement of a cascade downstream of the sluiceway stilling basin should be explored to ensure that TGP is reduced in the upper reaches of the river.

As in the previous annual reports, we again developed a model to relate delta P on the right bank at Rkm 0.6 to various physical factors and to the operation of Afterbay Dam. Variables selected for use in the model were determined by forward stepwise multiple linear regression analysis. The model developed included six variables, which is less than were used in 1985 or 1986. It includes:

$$\text{Delta P} = -505.60 - 1.32(T) - 21.41(SG1) + 33.60(SG3) + 22.82(RG1) - 41.52(RG2) + 10.43(RE - 3100.00)$$

$$r^2 = 0.6927 \quad \text{adjusted } r^2 = 0.6875$$

where: Delta P = hyperbaric pressure (mm Hg)
T = water temperature (C)
SG1 = sluice gate 1 opening (ft)
SG3 = sluice gate 3 opening (ft)
RG1 = radial gate 1 opening (ft)
RG2 = radial gate 2 opening (ft)
RE = river elevation (ft).

The predictive ability of the model as shown by the adjusted coefficient of determination was similar to the 1986 version and accounted for an additional 11% of the variation over the 1985 regession model. Significance tests of all variables and the regression analysis of variance demonstrated a linear relationship. Analysis of residuals suggested that assumptions of linearity, normality, and equality of variance were met. Other variables such as barometric pressure were forced into the equation, but were removed since they did not increase the predictive ability of the regression.

The 1987 annual mean values for water temperature (7.8 C), radial gate 1 (0.36 ft), radial gate 2 (0.87 ft), and river elevations (3160.29 ft) were used in the model while the openings of sluicegates 1 and 3 were varied by 0.1 ft increments from 0-6 ft in an attempt to predict what gate openings would result in problems. Based on these values, hyperbaric pressures determined from the model never dropped below 85 mm Hg. A delta P of 120 mm Hg was reached when sluicegate openings reached 2.9 ft. Temperatures in the model were then modified to determine the change associated with high (15.6 C) and low (2.0 C) values. At lower temperatures, a delta P of 120 mm Hg was achieved by sluicegate openings of 2.3 ft while at 15.6 C, the model did not predict reaching that level until approximately a 3.7 ft opening. An important problem associated with this model is its inability to predict lower gas pressures at very high gate openings. The development of another model for gate openings of approximately 5-6 ft should be attempted or other, more appropriate techniques applied.

As in 1985 and 1986, time constraints and data handling capabilities have forced us to examine Afterbay operations on a daily rather than an hourly basis. This method did not take into account the large daily change in delta P that can occur at Rkm 0.6, which regularly approached 50 mm Hg in early September (Figure 50). Data that include the diurnal fluctuations should be used to model gas production by Afterbay Dam and included in the final report. Also, a limited amount of data were collected in 1987 that may allow the application of a model (Johnson 1981) that predicts oxygen and nitrogen transfer from the sluice and spillways based on velocities, flow and stilling basin characteristics, tailwater depth, and initial gas pressures.

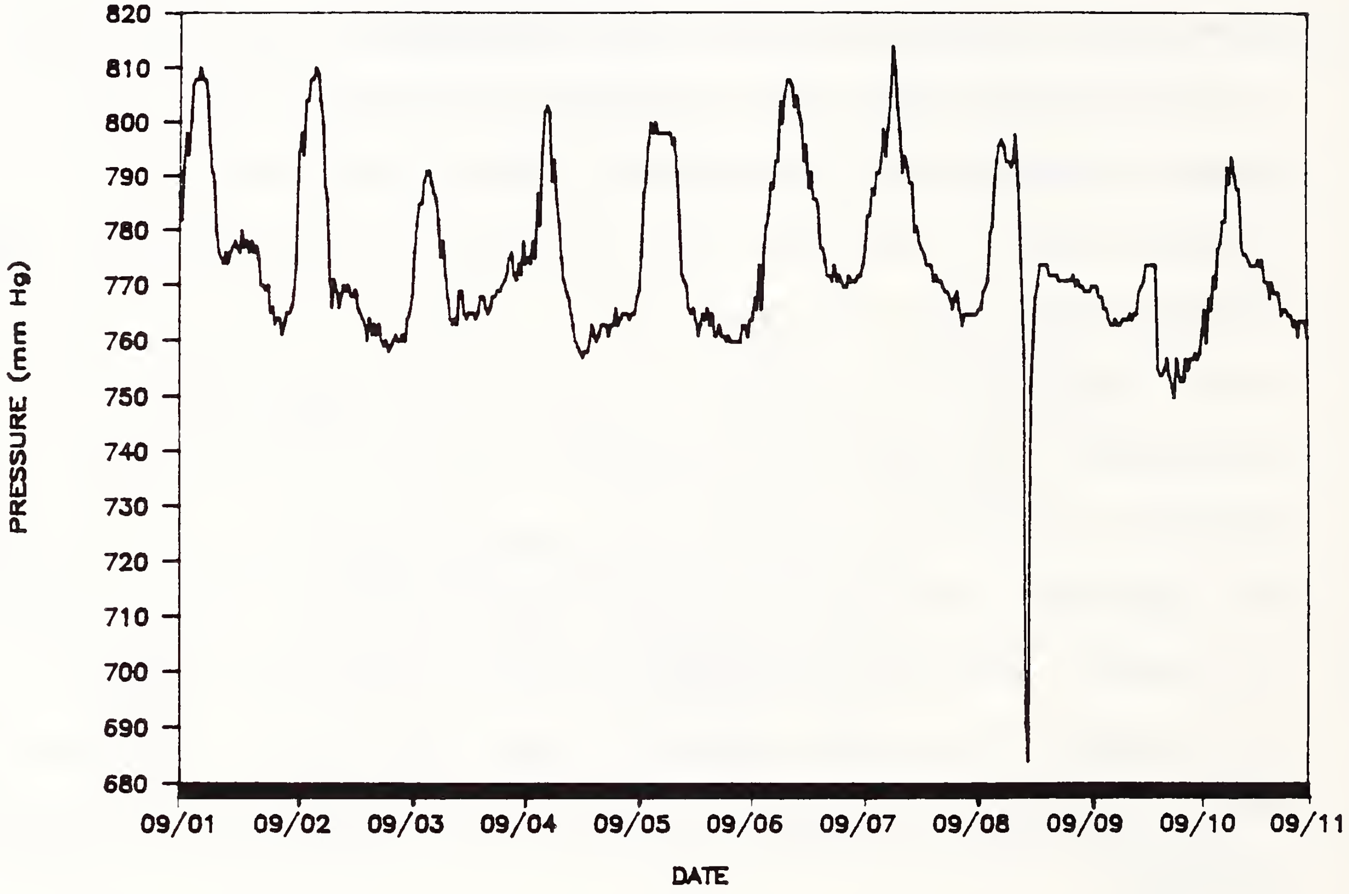


Figure 50. Daily fluctuations of uncorrected TGP measured by the Common Sensing tensionometer at Rkm 0.6 on the Bighorn River from 1-10 September, 1987.

IMPACT OF GAS SUPERSATURATION ON INVERTEBRATE COMMUNITY STRUCTURE

Documentation of gas bubble trauma (GBT) in insects is very limited. Nebeker (1976) and Fickeisen and Montgomery (1975) were able to induce GBT in stone flies during bioassays at relatively high gas supersaturation levels (125%-140%). This, however, does little to indicate the magnitude or range of effects exerted on zoobenthic communities, and the indirect effects on fish relying on them. The Bighorn River study offers an opportunity to examine the invertebrate communities while gas supersaturation is being constantly monitored.

Methods

Benthic Sampling

In an attempt to select two similar sampling riffles, the physical characteristics of four potential collection sites were analyzed. Because a control was not possible, keeping important parameters similar between sites will help determine community changes caused by gas supersaturation. Three transects, perpendicular to the current, were established at each site. Water depth and velocity, and substrate size were measured at 1.5 and 2 m intervals, respectively, along each transect. Riffles at Rkm 2.4 and at Rkm 14.5 were chosen due to their physical similarities and because of their proximity to early life history sites (Figure 51), where gas is monitored two or three times weekly. These sites represented areas where high and low levels of GBT were occurring in fish.

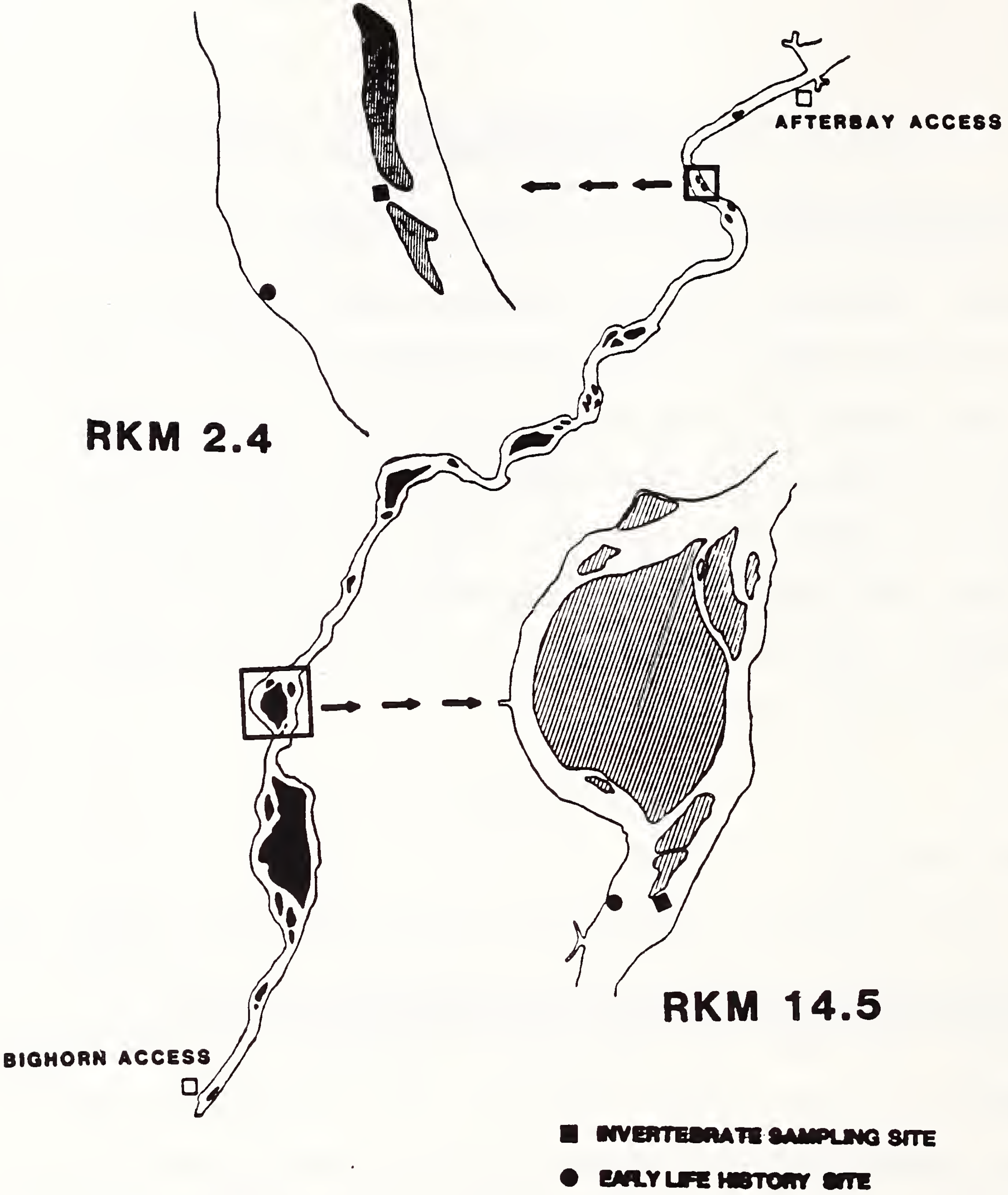


Figure 51. Bighorn River study area, illustrating channel characteristics at Rkm 2.4 and 14.5, and the proximity of invertebrate sampling sites to early life history sites, where gas was monitored two or three times weekly.

Benthic invertebrate samples were collected during three periods to describe zoobenthic community structure at each site. Sampling dates were chosen to represent pre- and post-runoff times, which correspond to low and high gas supersaturation and

GBT incidence in trout. The first collections were taken in August 1986 and represented post-runoff populations. In 1987 benthic samples were taken in April and in September. Twenty-five samples per site were taken during each collection period with the objective of reducing sampling variance and enhancing our ability to determine parameters important to specific taxa.

Benthic sampling locations were randomly chosen by dividing riffles into 1 m^2 grids and using computer generated random numbers to select sample sites. Samples were collected by imbedding a 0.085 m^2 modified Hess sampler into the substrate to a depth of 5-10 cm. All rocks with periphytic algae were individually scrubbed with a soft bristled brush, examined to ensure organisms were absent, then removed from the sampler. Remaining substrate was agitated with a steel rod to a depth of 7-10 cm, before removal of the sampler. Before each sample was taken, water velocities (0.6 depth and 5-7 cm above the substrate) and depth were measured using a Marsh-McBurney current meter, and a top-setting rod. Only water velocities at 0.6 depth were collected during the 1986 sampling period. During all three collection periods, samples were gathered from each site over a 2 d period.

Invertebrate sorting in the lab was facilitated by straining samples through a series of three sieves (8.0, 1.0, and 0.5 mm mesh size), before picking. This increased sorting efficiency by allowing invertebrates to be picked from similarly sized material. Due to sample richness and the time required to pick them (approximately 15 hr per sample), only 36 of the spring and fall 1987 samples will be analyzed, and the small materials from these will be subsampled before sorting.

Vegetative materials from the 1986 samples were dried in an oven at 105^{o}C for 24 hr. The dry weight values provided a basis for comparing vegetative biomass between samples. This will also be done with 1987 samples.

Drift Sampling

Fickeisen and Montgomery (1975) noted that while direct mortality due to GBT was not apparent in the aquatic insects they tested, several taxa experienced bouyancy problems due to gas bubbles adhering to their bodies. Thus drift samples were taken during the May and September 1987 collection periods to enable evaluation of drift rates between sites.

Replicating drift samples just after dark (period of peak drift) increases sampling efficiency over 24 hr sampling schemes, reducing the number of samples required to quantify invertebrate abundance (Allan and Russek 1985). Thus four synchronized drift samples were taken at the lower end of the two study sites, on two consecutive nights. The nets had 0.15 m^2 openings and had a mesh size of 500 microns. Each net sampled the entire water column. Water velocities were measured (0.5 depth) at the mouth of each net at the beginning, middle and end of each sample. Sample duration was 1 hr the first night in May 1987, but was reduced to 0.5 hr the following night, and during the September sampling. All benthic and drift samples were preserved in

Kahle's solution containing rose bengal to facilitate sorting in the lab.

Periphyton Collection and Analysis

Periphyton samples were taken during both 1987 sampling periods. During April 1987, standing crop of periphyton appeared to vary substantially within collection sites. To reduce sampling bias and minimize variance, upstream and downstream sites were partitioned into subsections based on visual differences in periphyton abundance, and mapped (Figure 52). Following analysis, subsections not found to be significantly different were combined. These data will be helpful in making comparisons of invertebrate communities from similar habitat types.

Periphyton sampling sites, within subsections, were chosen by throwing a steel rod, marked on one end, into the water, and collecting the rock nearest the marked end. Periphyton was scraped off the rock, placed in a labeled plastic bag, put on ice in a cooler, and later frozen to preserve for analysis in the lab. The periphytic attachment area was determined by taking two measurements - essentially length and width - to provide a basis for comparison between samples. In May, 42 and 39 samples were collected from the upper and lower sites respectively, and the number of periphyton samples collected were proportioned according to subsectional area. In September both riffles appeared more homogeneous and were not partitioned. Forty samples were collected from each site. Periphyton analysis

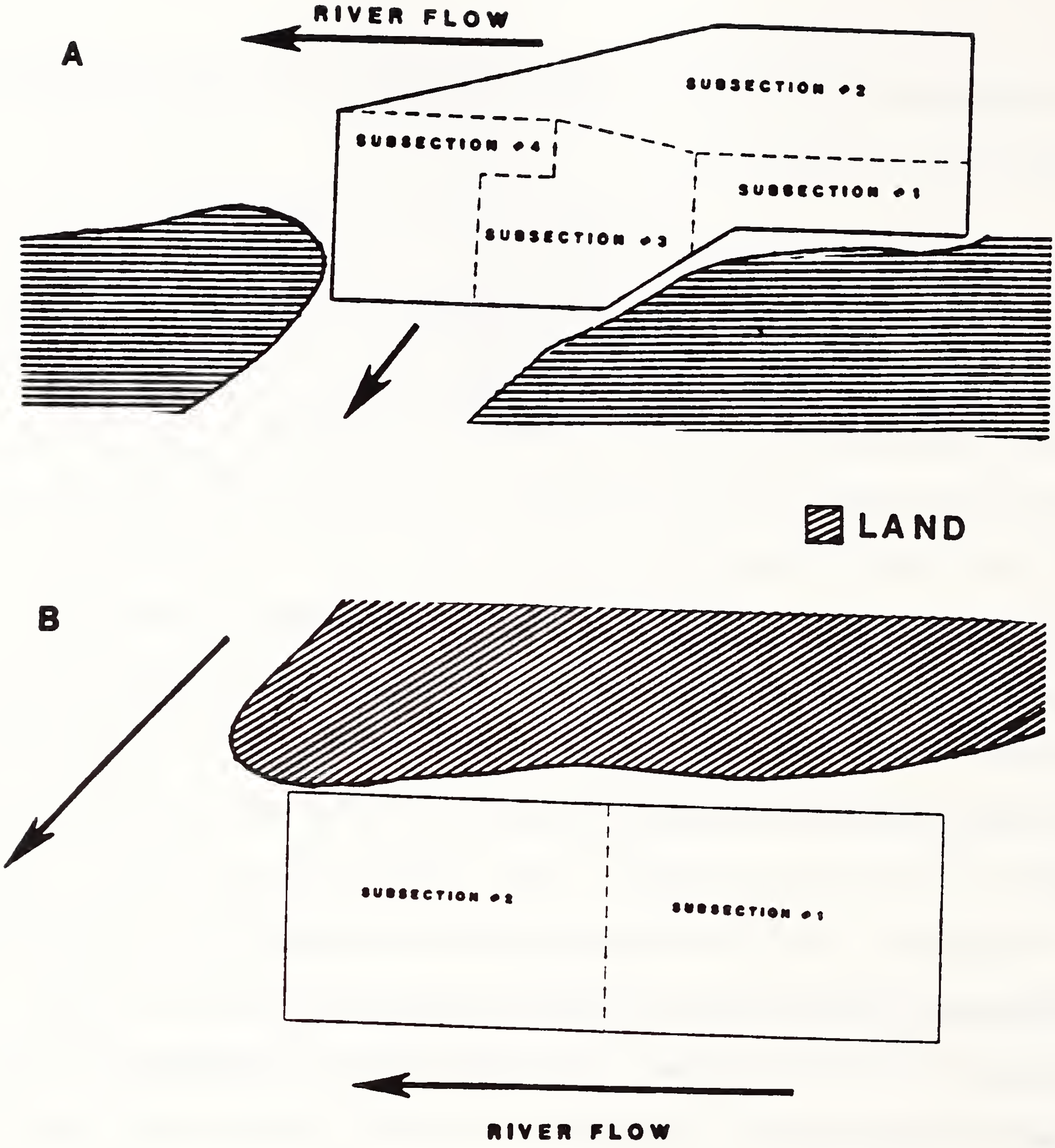


Figure 52. Division of invertebrate sampling sites at (A) Rkm 2.4 and (B) 14.5 into subsections for periphyton analysis, April, 1987.

involved determination of chlorophyll A concentration as well as dry weight and ash-free dry weight.

Chlorophyll and Dry Weight

Each periphytic mass was thawed, blotted with paper towels, and weighed. Three subsamples of approximately 0.2 g were removed and weighed for chlorophyll extraction and analysis. Subsamples were placed in a centrifuge tube with 10 ml of extractant (DMSO:90% acetone), agitated, then placed in a dark freezer for 24 hr. Upon removal, they were centrifuged for 10 min. One milliliter of the resultant chlorophyll solution was then diluted with an additional 5 ml of extractant. Spectrophotometry was done using a spectronic 20 spectrophotometer, and methods described by Wilkinson (1983) were used to correct for absorbance by phaeopigments. The following formula (modified from Wilkinson 1983) was used to determine chlorophyll A concentration per unit weight of vegetation:

$$C = (E_a - E_b) \cdot 27.31 \cdot v/m \cdot l$$

Where: C = Chlorophyll A concentration (ug chlor per g of vegetation)
E_a = Extract absorbance at 665 nm before acidification minus absorbance at 750 nm.
E_b = Extract absorbance at 665 nm after acidification minus absorbance at 750 nm.
27.31 = Constant used for (90% acetone:DMSO) extractant
v = volume of extractant solution used in ml.
m = wet weight (in grams) of vegetation chlorophyll is extracted from.
l = pathlength of cuvette (usually 1 cm).

The remaining vegetative mass (following removal of 0.2 g samples) was placed in a drying oven at 105°C for 24 hr. Dry weights were taken prior to ashing in a muffle furnace to at 500° C for 24 hr. A final weight was taken to enable determination of ash-free dry weight.

Suspended Particulate Organic Matter

Suspended particulate organic matter (SPOM) samples were taken at each site, during both sampling periods in 1987, to evaluate differences in food availability for different filter-feeding organisms. Analysis includes comparing availability of various size categories of particulate organics between sites. Data will be used as another way to compare similarity of collection sites.

To collect SPOM a Wisconsin-type plankton net with a 12 cm mouth diameter and 80 um mesh was attached to a metal rod driven into the substrate. The net was positioned approximately midway in the water column. Water velocities at the net mouth were measured immediately after net placement using a Marsh-McBurney current meter. Net placement and removal times were recorded. Collection time was approximately 30 min for each sample. Three and four samples were collected from each riffle during the May and September collection times, respectively. All SPOM samples were cared for in the same manner as the periphyton samples. Analysis on these samples will involve sieving, drying, and ashing to determine ash-free dry weight of various SPOM size groups.

Results and Discussion

Forty-eight of the 1986 benthic samples have been picked (2 were inadvertantly mixed). The medium and large materials from 34 of the spring 1987, and 30 of the fall 1987 samples have also been sorted.

The taxonomic list at this time, (appendix 1) consists of five genera of Ephemeroptera, three genera of Trichoptera, two genera of Plecoptera, one genera of Coleoptera, two genera of Amphipoda, one genera of Hirudinea, and one genera of Gastropoda. Dipterans are represented by the families Simuliidae (one genus), Chironomidae, Tipulidae, Ceratopogonidae, and Sciomyzidae. Oligochaetes and Planaria were also present.

Community composition between sites was similar, but a significant change in relative abundance of taxa existed. Of five taxa quantified from the 1986 samples, four were significantly different between sites (Table 35). Three were more abundant downstream, and one was more numerous upstream.

Table 35. Abundance estimates (number per m^2) of five genera of invertebrates, collected from two sites on the Bighorn River, in August 1986. 95% CI given in parentheses.

	Tricorythodes[a]	Serratella[a]	Gammarus[a]	Hyallela	Simulium[a]
Rkm 2.4	1459 (1166-1752)	539 (446-632)	4127 (2997-5270)	37 (14-60)	2175 (1219-3131)
Rkm 14.5	12673 (11041-14305)	1548 (1323-1845)	42 (40-44)	25 (15-35)	5610 (2178-9042)

[a] -denotes taxa exhibiting a significant difference in abundance between sites (alpha=0.05).

Tricorythodes increased from 124 individuals per sample at Rkm 2.4 to 1077 at Rkm 14.5. Simple regressions were run using Tricorythodes as the dependent variable against the independent variables, water velocity (0.6 depth) and depth, and dry weight (DW) of vegetation present in the benthic samples. Results indicated that Tricorythodes abundance most closely correlated with velocity at the upstream ($R^2 = .1257$, $P = .0821$) and downstream ($R^2 = .1839$, $P = .0411$) sites. This parameter, however, seems to explain only a small portion of the observed variation.

Serratella abundance, also increased significantly downstream. The mean number per sample at Rkm 2.4 was 46 opposed to 135 at Rkm 14.5. No significant correlation was found between Serratella abundance and any of the parameters measured at Rkm 14.5, however, at Rkm 2.4 there was a significant positive correlation with velocity ($R^2 = .2068$, $P = .0293$).

Other mayflies occurring in the Bighorn River that have not been completely quantified are Baetis tricaudatis, Ephemerella sp., and Choroterpes sp. Baetis are abundant at the upper collection site. For example, one sample (0.085 m^2) contained 2270 individuals, and the average sample probably contains well in excess of 1000. Baetis abundance decreased downstream, though it was still common.

Ephemerella was not present in any of the 1986 samples, due to their early summer emergence, but was present in samples from spring 1987. Serratella and Ephemerella may be filling the same or nearly the same niche but are separated in the timing of their life cycles. Choroterpes was rare and occurred in only a few samples.

Gammarus lucustris and Hyalella azteca were present at both sampling sites. Gammarus decreased in numbers downstream, with an average of 351 per sample at Rkm 2.4 to 4 per sample at Rkm 14.5. Regression analysis showed a positive correlation between abundance and depth ($R^2 = .2215$, $P = .0203$) and DW ($R^2 = .4768$, $P=.0000$) at the upstream site. Downstream there was no correlation with depth and the correlation with DW was not as strong ($R^2 = .2286$, $P = .0210$). Gammarus lucustris is described by Smith (1973) as a cold water stenotherm. It is likely that thermal constancy near the dam, coupled with vegetative differences between sites, is responsible for Gammarus' reduction downstream.

Hyalella showed no significant change in abundance between sites (three and two per sample at Rkm 2.4 and Rkm 14.5, respectively). The only parameters significantly correlated with abundance were velocity ($R^2 = 0.2479$, $P = .0113$) at Rkm 2.4, and DW ($R^2 = .1827$, $P = .0419$) at Rkm 14.5.

Significantly fewer black fly larvae were observed at the upstream site. Samples averaged 185 Simulium at Rkm 2.4 compared with 477 at Rkm 14.5. There was no significant correlation between abundance and any of the independent parameters measured at Rkm 2.4. At Rkm 14.5, however, a positive correlation between DW and abundance ($R^2=.5044$, $P=.0000$) existed. The existence of a significant correlation downstream, while none existed upstream, suggests a response by Simulium to vegetative differences between sites. During August 1986 macrophytes at Rkm 2.4 were only occasionally present, but were quite common at Rkm 14.5. Numerous Simulium were observed attached to Potomageton stalks. This probably positions them in the water column where filter feeding is less inhibited by the presence of filimentous algae.

Since the parameters that correlated with individual taxon abundance often changed between sites, physical differences between sampling areas are likely influencing community structure. Of the five taxa evaluated to date, only Tricorythodes and Serratella show possibilities of being affected by gas supersaturation. These taxa, as well as others, will be evaluated using gas supersaturation bioassays.

Periphytic Ash Free Dry Weight and Chlorophyll A Concentration

Ash free dry weight analysis of the April 1987 periphyton samples, showed no significant difference between the four upstream subsections (significance = 0.0734). Thus, they were combined and treated as one. Downstream subsections, however, showed a strong significant difference (P = 0.0000). Comparison between sites indicated the periphyton in the upstream site was significantly less than in downstream subsection 2 (P = 0.0004), but not significantly different from downstream subsection 1 (P = 0.5207).

Chlorophyll A weight analyses for the May 1987 samples indicated that a significant difference existed between subsections 1-4 at Rkm 2.4 (Significance = 0.0242). Another test run on subsections 1-3 showed no significant difference (significance = 0.6473). Thus, subsections 1-3 were combined and treated apart from subsection 4. Subsections at Rkm 14.5 were also significantly different (P = 0.005). Comparison between sites showed no significant difference between upstream subsections 1-3 and downstream subsection 2 (P = 0.2560). This also was the case between upstream subsection 4 and downstream subsection 1 (P = 0.3009).

Preliminary evaluation of the periphyton data does little to relate periphyton to benthic invertebrates. When the April 1987 benthic samples are quantified, however, perephyton results will allow comparison of invertebrate samples from the most similar habitats. This should provide insight to community changes related to habitat, verses those related to gas supersaturation.

PHYSIOLOGY VERSUS HABITAT SELECTION

Brown trout in the Bighorn River have a higher incidence of external symptoms of GBT than observed in rainbow trout. We hypothesized that this could be due to physiological differences between the species or, alternatively, to differences in habitat preferences.

Physiology studies are being conducted at the University of British Columbia to determine thresholds of total gas pressure (TGP) required to 1) initiate bubble growth in the vascular system, 2) produce over-inflation of the swim bladder, and 3) develop bubbles in the buccal cavity of small fish.

Physiology Studies

At the University of British Columbia, Larry E. Fidler has completed a detailed review of the literature on supersaturation in fish. In addition he has completed a lengthy series of physiological studies of bubble growth in fish exposed to supersaturated water. The results of this work indicate the existence of two distinct thresholds for bubble growth in salmonids. The first threshold, as indicated in the literature and confirmed by the studies at U.B.C., occurs at a water Total Gas Pressure of approximately 1.10 Atmospheres and is independent of water p02. The second threshold is dependent on water p02 and is about 1.16 Atmospheres at a p02 of 185 mmHg., sea level conditions and zero depth. Between the thresholds of 1.1 to 1.16 Atmospheres, there is no clear relationship between survival and water p02. This may be due to the fact that available data are restricted to a narrow range of p02 values. The symptoms observed in this range of total gas pressures suggest that elevated levels of p02 should enhance survival. Above a TGP of 1.16 Atmospheres, there is clear evidence that survival increases with increasing water p02. The reason for this increase becomes clear when the symptoms associated with the thresholds are examined.

At a water TGP of 1.1 Atmospheres, extra-corporeal bubbles begin to form within the gill lamella. The bubbles lodge between the primary and secondary lamella, blocking the respiratory water flow. As TGP increases, the number and size of these bubbles increases, causing yet further blockage. At this threshold, sub-dermal bubble growth on the body surfaces of fish also begins. This form of bubble growth becomes quite pronounced in the buccal cavity where large blisters form on the roof of the mouth and near the gill rakers at the entrance to the gills. The blisters further block the flow of water through the gills and compound the problems created by bubble growth in the lamella. The physiological symptoms are as would be expected for reduced respiratory water flow. There is a steady decline in arterial p02 and pH with time. In addition, there is a gradual increase in hematocrit. The increase, however, is not as dramatic as is encountered above the second threshold as will be described shortly. With reduced respiratory water flow, it is clear that higher water p02 levels will tend to offset the effects of blockage and increase survival time.

Figures 53 and 54 show the typical response of arterial p02,

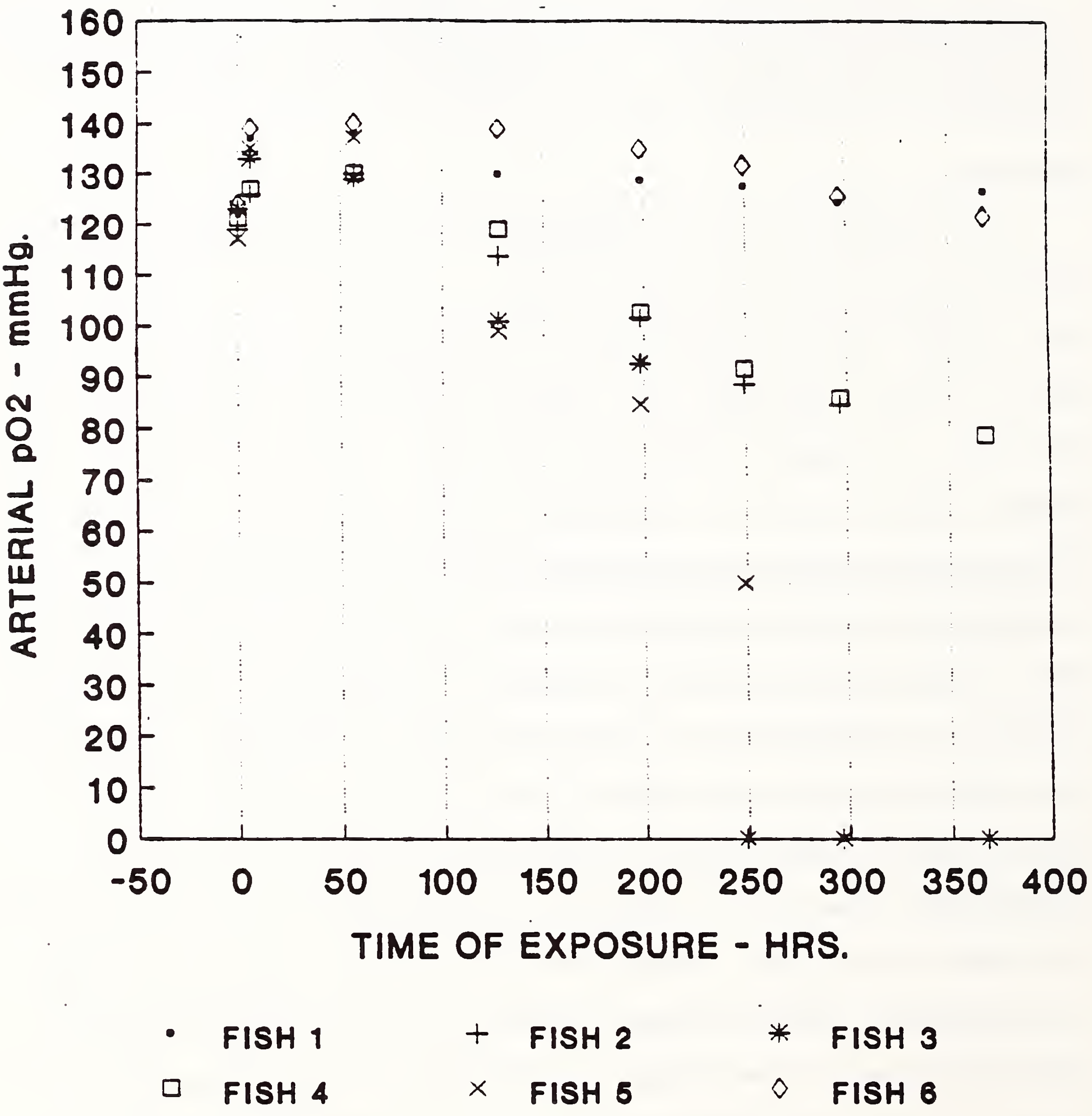


Figure 53. Arterial blood pO2 variation with time in rainbow trout exposed to water TGP of 1.12 Atmospheres with a pO2 of 175 mmHg.

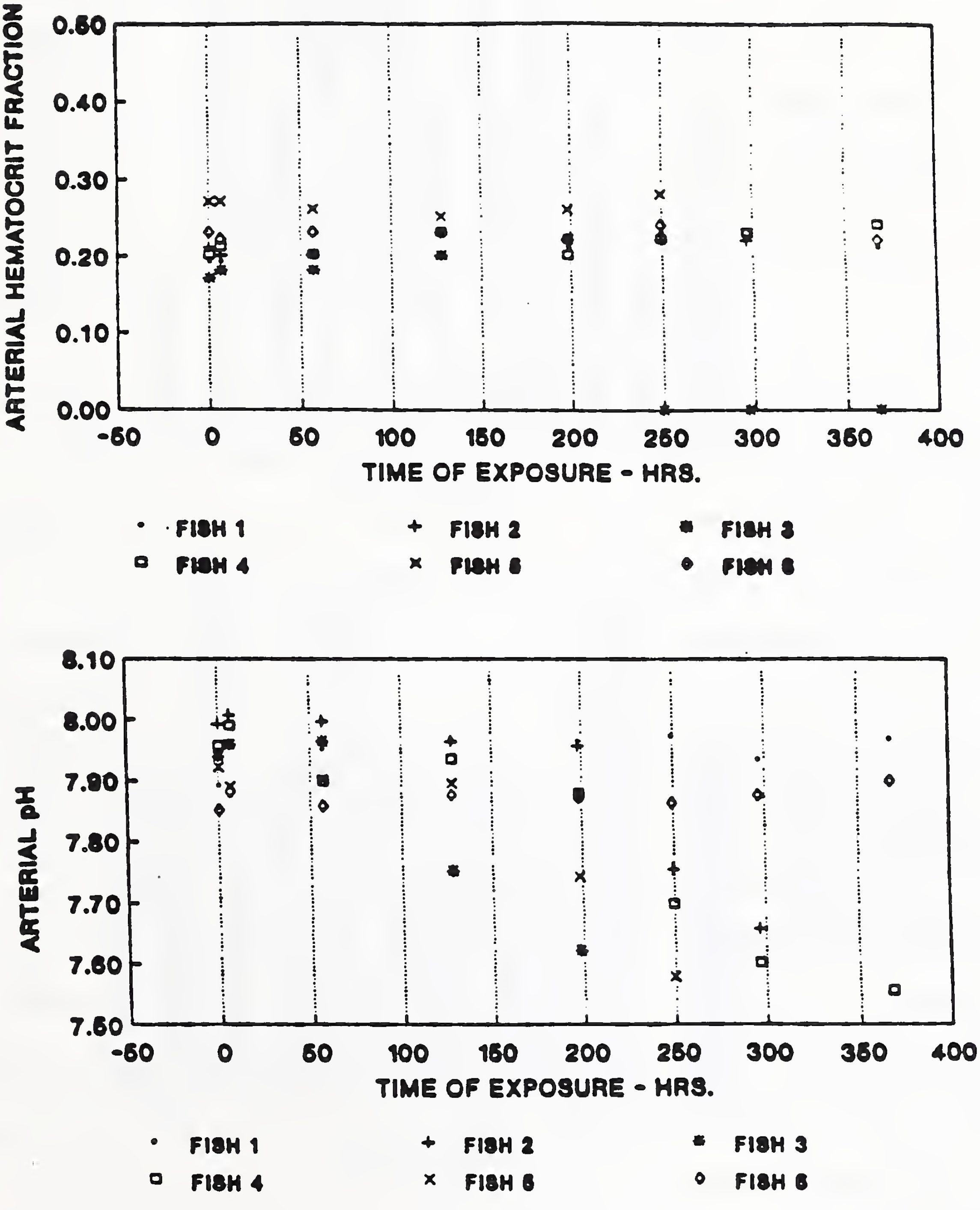


Figure 54. Arterial blood hematocrit and pH variation with time in rainbow trout exposed to water TGP of 1.12 Atmospheres with a pO2 of 175 mmHg.

pH and hematocrit for six fish exposed to a water TGP of 1.12 Atmospheres and a water p02 of 175 mmHg. The measurements were made by way of indwelling dorsal aorta cannula. In addition, six non-cannulated fish were tested along side the cannulated fish at the same conditions of supersaturation. Figure 55 shows the relative severity of symptoms observed at death for these conditions of TGP and p02. In general, the time of survival is reduced as water TGP increases.

A water TGP of 1.16 Atmospheres and a p02 of 185 mmHg is the approximate threshold for intra-vascular bubble growth at sea level conditions and zero water depth. The observed experimental thresholds, as indicated by the threshold equations of Larry Fidler, are dependent on water p02 (See earlier progress reports for discussions of threshold equations). As the equations indicate, the thresholds for cardiovascular bubble growth increase as water p02 increases. In addition, the time of survival increases with increasing water p02. When this threshold is reached, clear evidence of bubble growth in the filamental arteries of the primary lamella can be observed microscopically. In addition, dramatic declines in arterial blood p02 and pH occur along with large increases in hematocrit. The increases in hematocrit at the lower threshold of 1.1 Atmospheres suggest recruitment of red blood cells from the spleen. However, above 1.16 Atmospheres the increase in hematocrit is significantly larger than can be accounted for by RBC recruitment. This would suggest that water is being forced

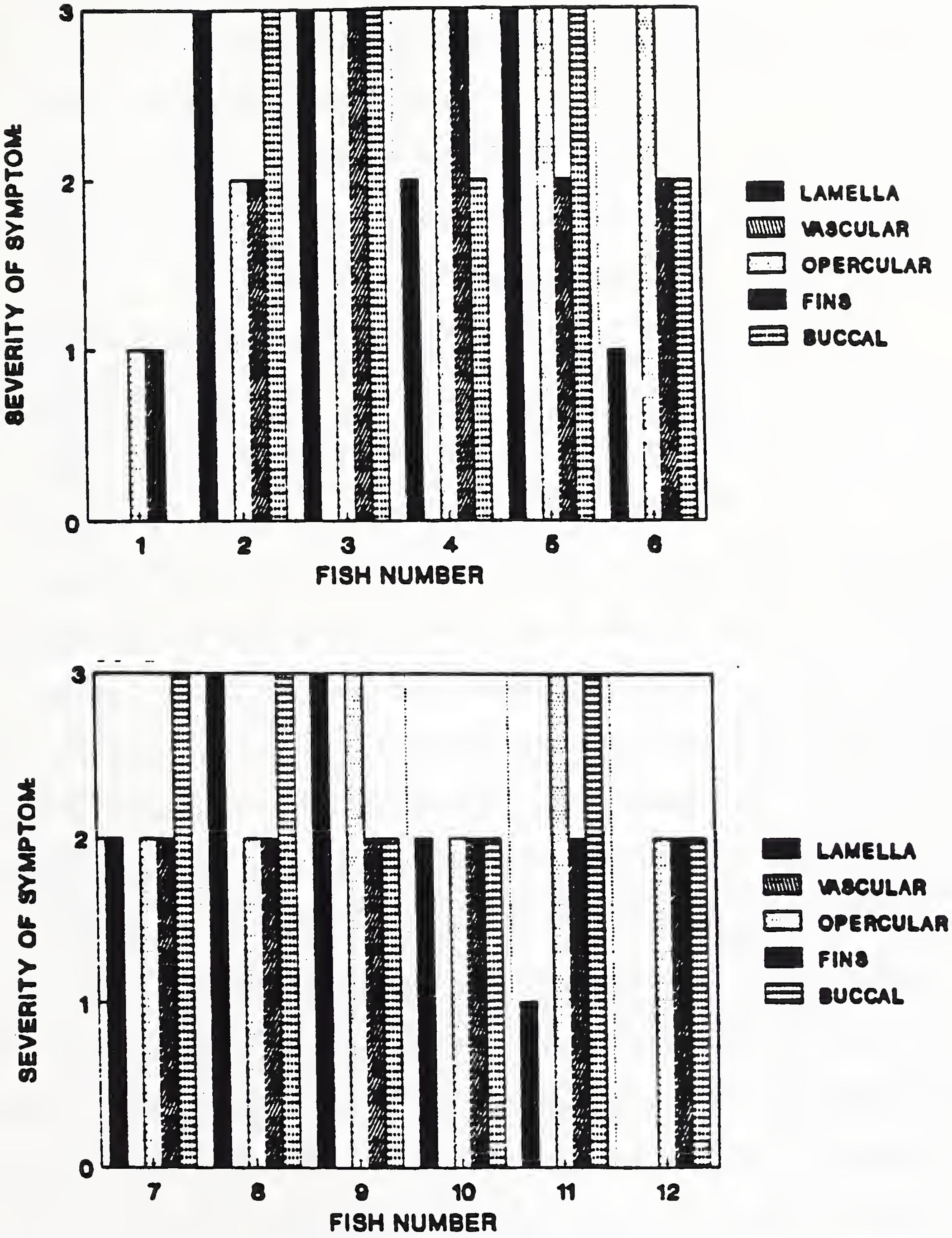


Figure 55. Relative severity of gas bubble truma symptoms observed at time of death of six cannulated (1-6) and six non-cannulated (7-12) rainbow trout exposed to water TGP of 1.12 Atmospheres with a pO2 of 175 mmHg.

out of the vascular compartments by the growing bubbles. Figure 56 shows the declines in arterial p02 and pH for six cannulated fish at a water TGP of 1.19 Atmospheres and a p02 of 201 mmHg. Figure 57 shows the variation in hematocrit with time of exposure. Figure 58 shows the relative severity of symptoms at death for the six cannulated and six uncannulated fish.

The primary difference between the two bubble growth thresholds is the time to mortality. At water TGP between 1.1 and 1.16 Atmospheres, death usually requires more than 100 h to occur. Often several hundred hours are required before a 50% mortality condition is reached. Contrasting with this is the relatively short times to mortality associated with water TGP levels above 1.16 Atmospheres. At these higher levels, significant mortalities can occur in less than 100 h. This is illustrated in Figure 59 which shows the results of three experiments. In each experiment 6 to 12 fish were exposed to a water TGP of 1.15 Atmospheres with different water p02's. It can be seen that at a water p02 less than 125 mmHg, the time to mortality is significantly shorter than at the higher p02 levels. This suggests that a threshold exists between 70 and 100 mmHg, p02 and a TGP of 1.15 Atmospheres. Similar results were obtained by Rucker (1975) for Coho salmon at a water TGP of 1.19 Atmospheres and various p02 levels. Ruckers results, shown in Figure 60, clearly show a threshold between a water p02 of 250 and 275 mmHg.

The results of the experimental studies of bubble growth thresholds is summarized in Figure 61 where the thresholds as

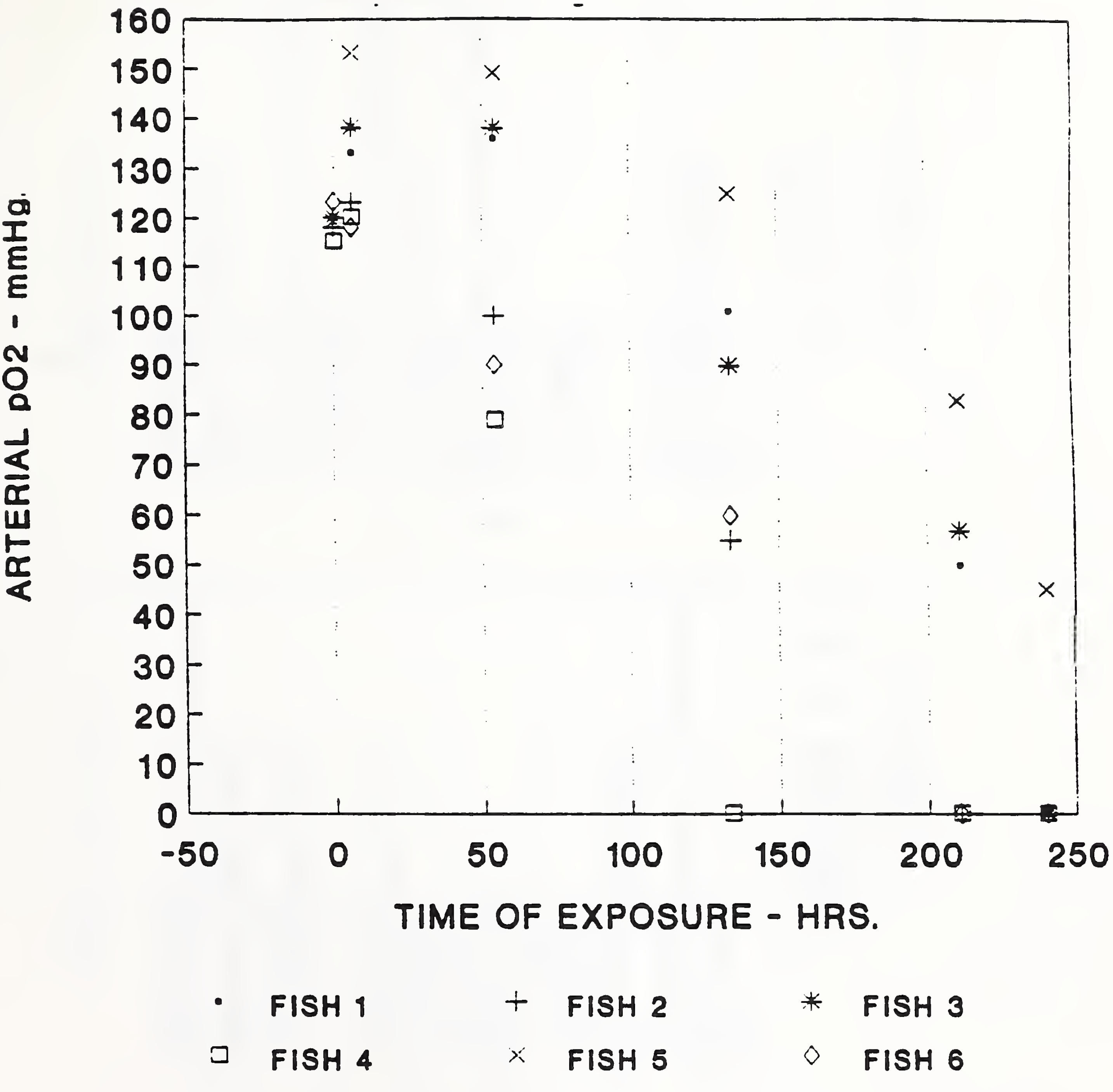


Figure 56. Arterial blood pO2 variation with time in rainbow trout exposed to water TGP of 1.17 Atmospheres with a pO2 of 195 mmHg.

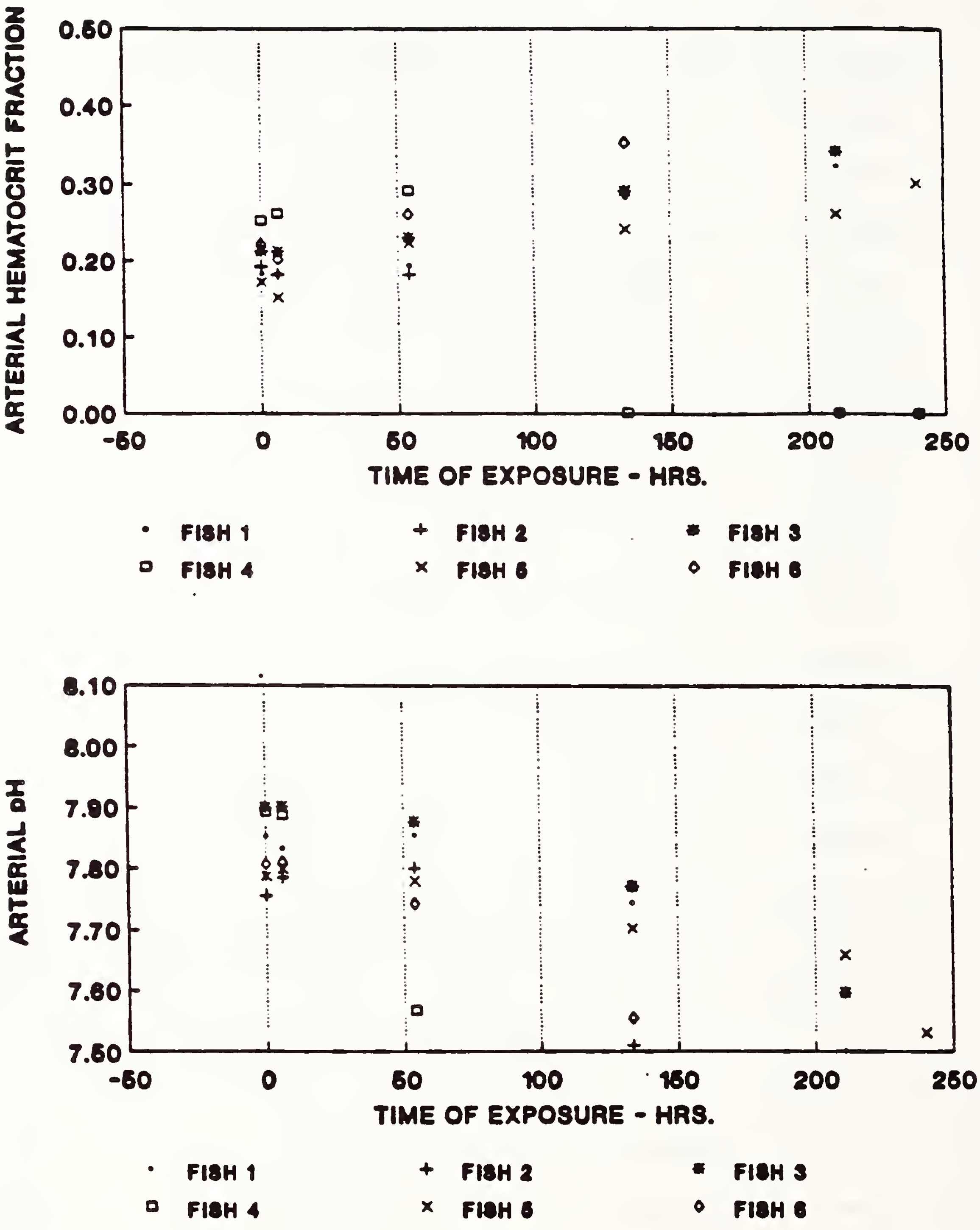


Figure 57. Arterial blood hematocrit and pH variation with time in rainbow trout exposed to water TGP of 1.17 Atmospheres with a pO2 of 195 mmHg.

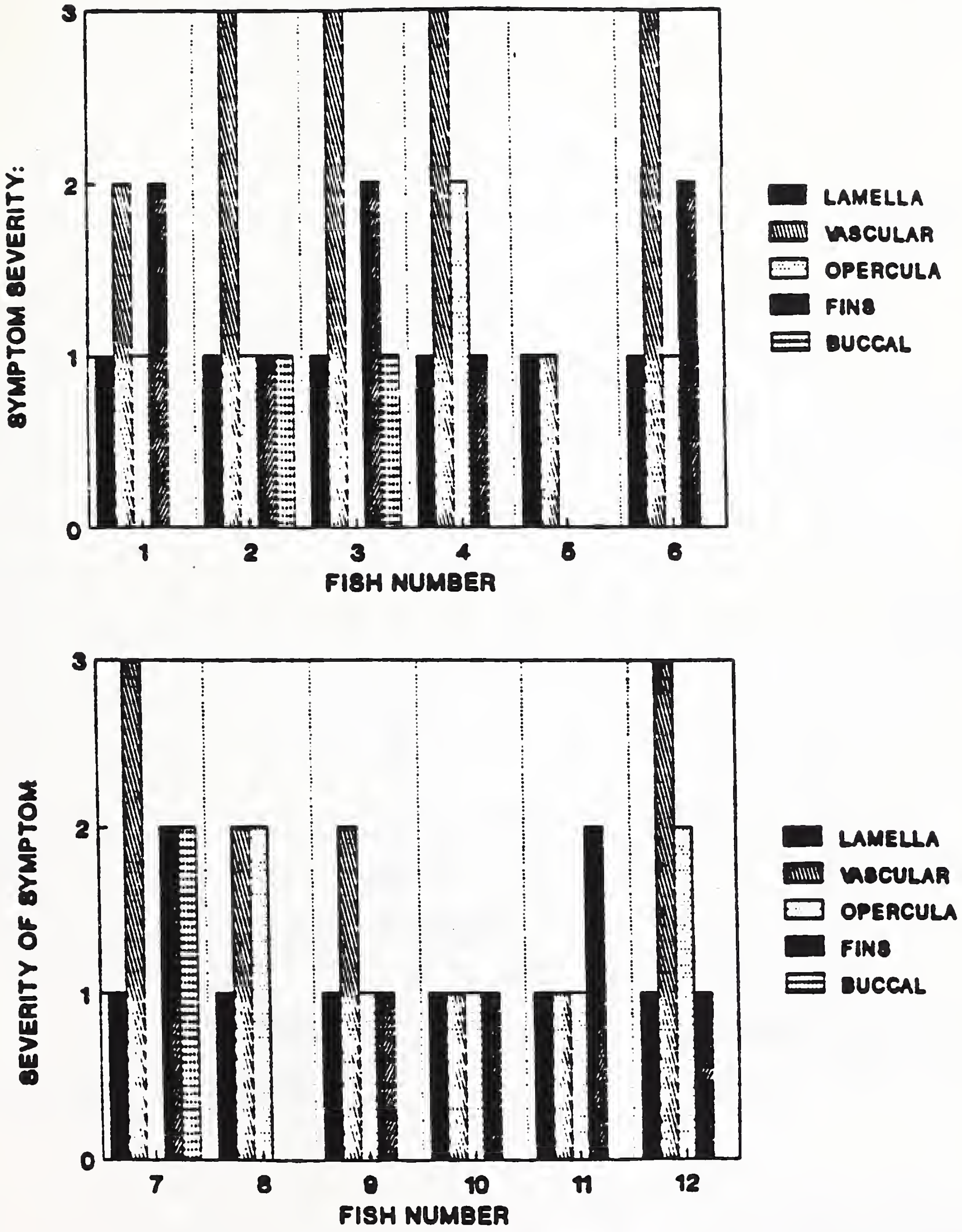


Figure 58. Relative severity of gas bubble trama symptoms observed at time of death of six cannulated (1-6) and six non-cannulated (7-12) rainbow trout exposed to TGP of 1.17 Atmospheres with a pO2 of 195 mm Hg.

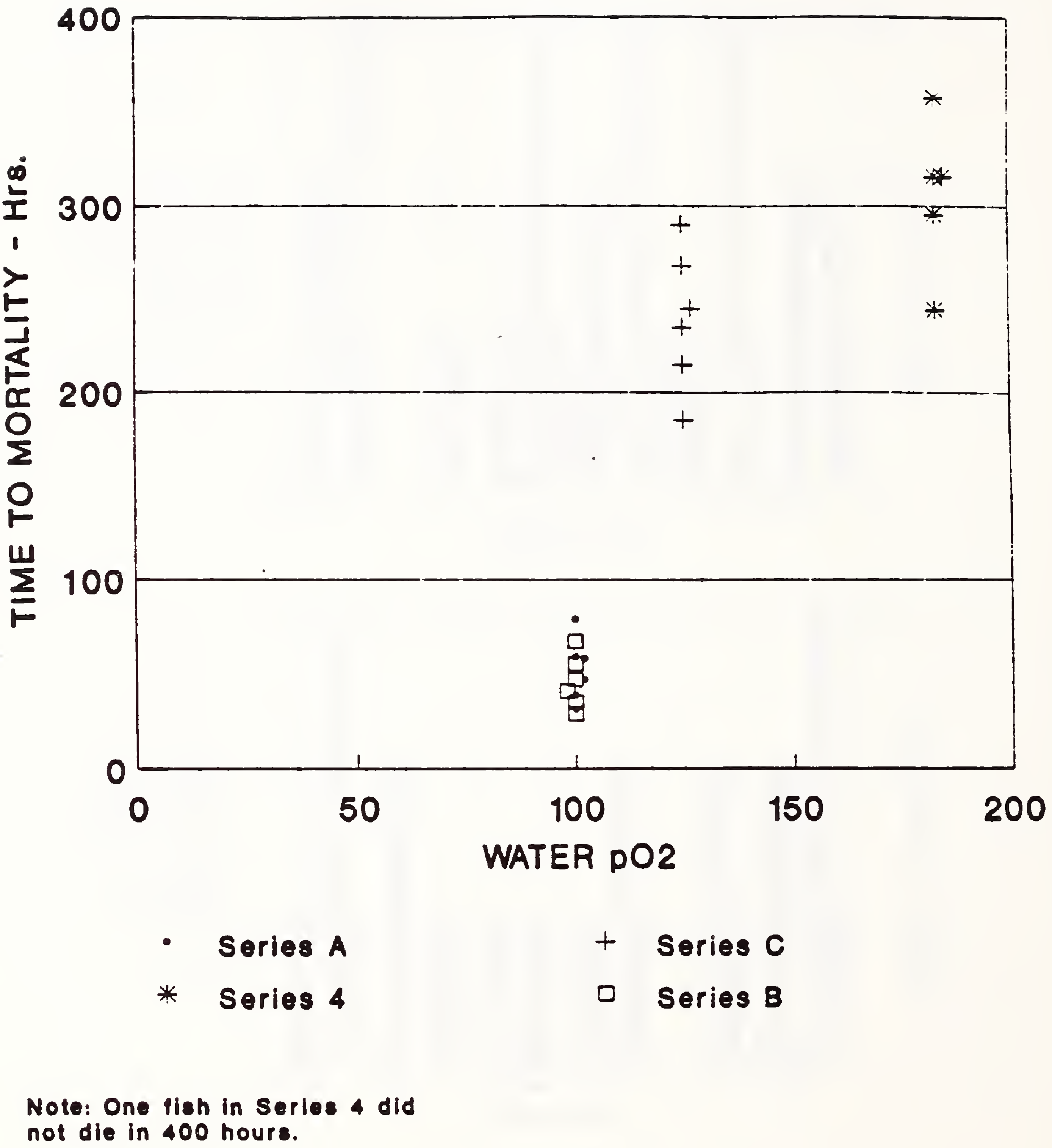


Figure 59. Time to mortality of rainbow trout exposed to water TGP of 1.15 Atmospheres and three different levels of pO2.

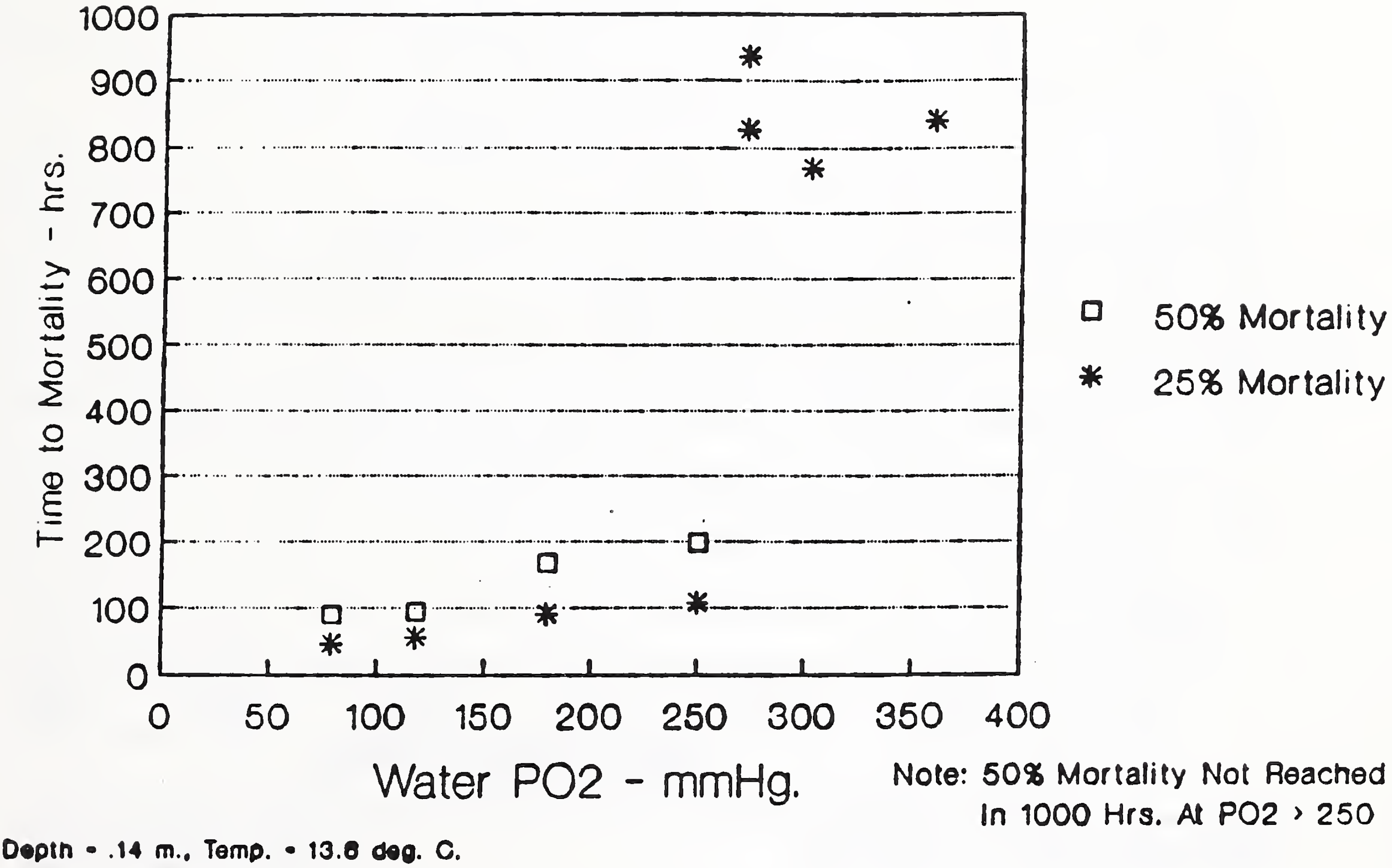
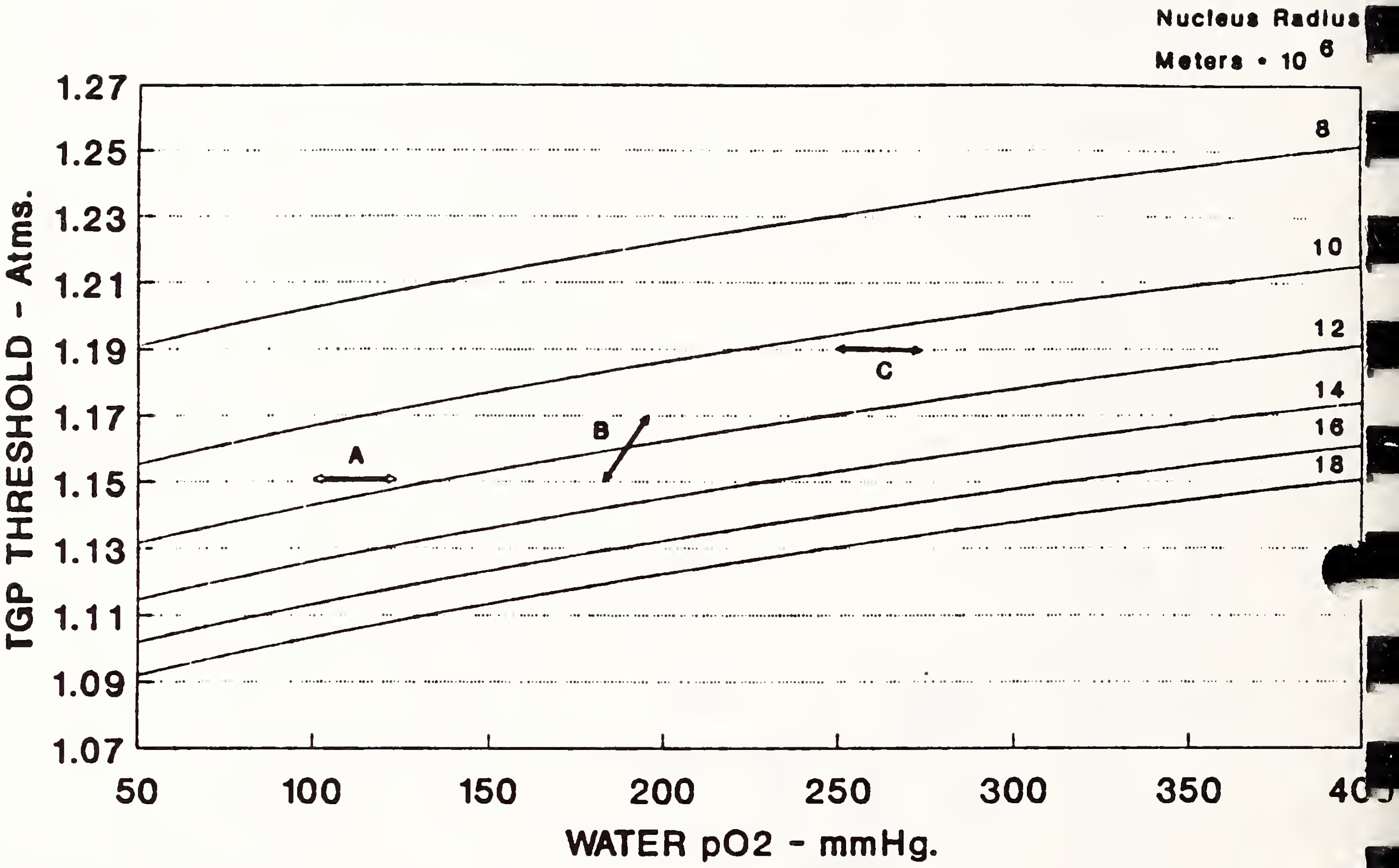


Figure 60. Time to mortality of coho salmon exposed to water TGP of 119.3 % and various pO2 levels (Ricker 1975).



Water Depth • 0.0 m. F • 0.79
Water Temperature • 5 - 15 deg. C.
Atmospheric Pressure • 760 mmHg.

[A & B - Rainbow trout] Fidler (1988)
[C - Coho salmon] Rucker (1975)

Figure 61. Total gas pressure thresholds for bubble growth in arterial blood as a function of pO2 and nucleus radius.

determined by this work along with those of Rucker (1975) are shown in relation to the predictions of the theoretical threshold equations. The threshold equations are presented in terms of the radius of the unknown nucleation sites (See earlier progress reports for discussion of nucleation sites). It can be seen that the results of this work and that of Rucker (1975) clearly indicate a threshold nucleation site radius of about 12 uM.

Other work at U.B.C. by Shrimptom, Fidler and Randall (1988) has defined the thresholds for overinflation of the swim bladder. Figure 62 shows the results of measuring the rate of swim bladder inflation in fish exposed to supersaturated water. This was accomplished by cannulation of the swim bladder and monitoring swim bladder pressure. In the figure, the square symbols indicate a positive inflation rate while the plus symbols indicate a negative inflation rate (deflation). Clearly the region between the two indicate the threshold for overinflation. Also plotted in the figure is the theoretical threshold as predicted from the equations by Fidler. It is seen that the theoretical predictions are quite consistent with the experimental data.

The results of both the swim bladder overinflation and bubble growth studies are summarized in Figure 63. The threshold equations are plotted as a function of water p02 for sea level conditions and zero water depth. It is seen that there is clear separation of the thresholds over the range of water p02 values shown. It should be emphasized that with each threshold there are also characteristic ranges of time to mortality. In general,

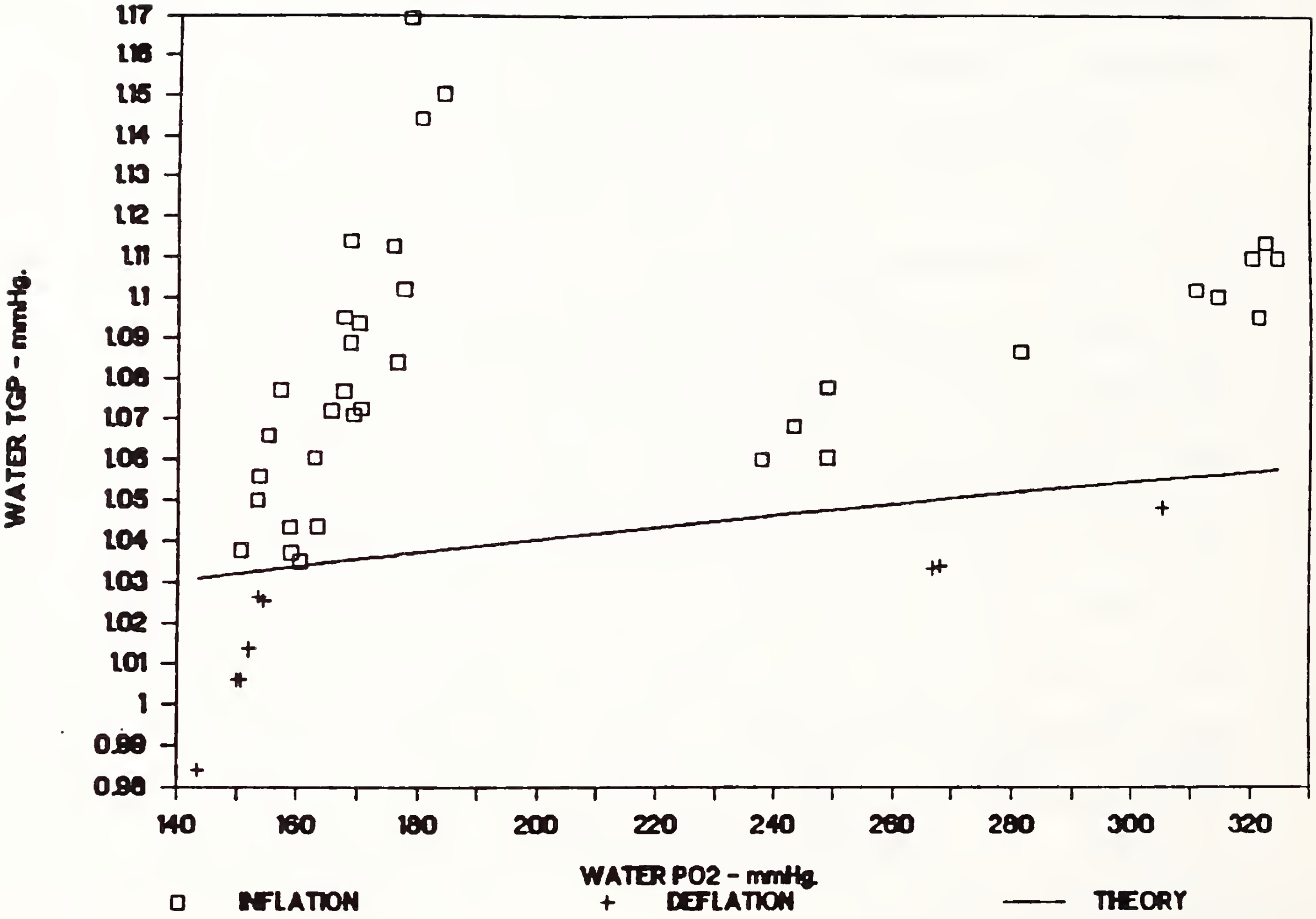


Figure 62. Influence of total gas pressure and water pO2 on swimbladder inflation in rainbow trout.

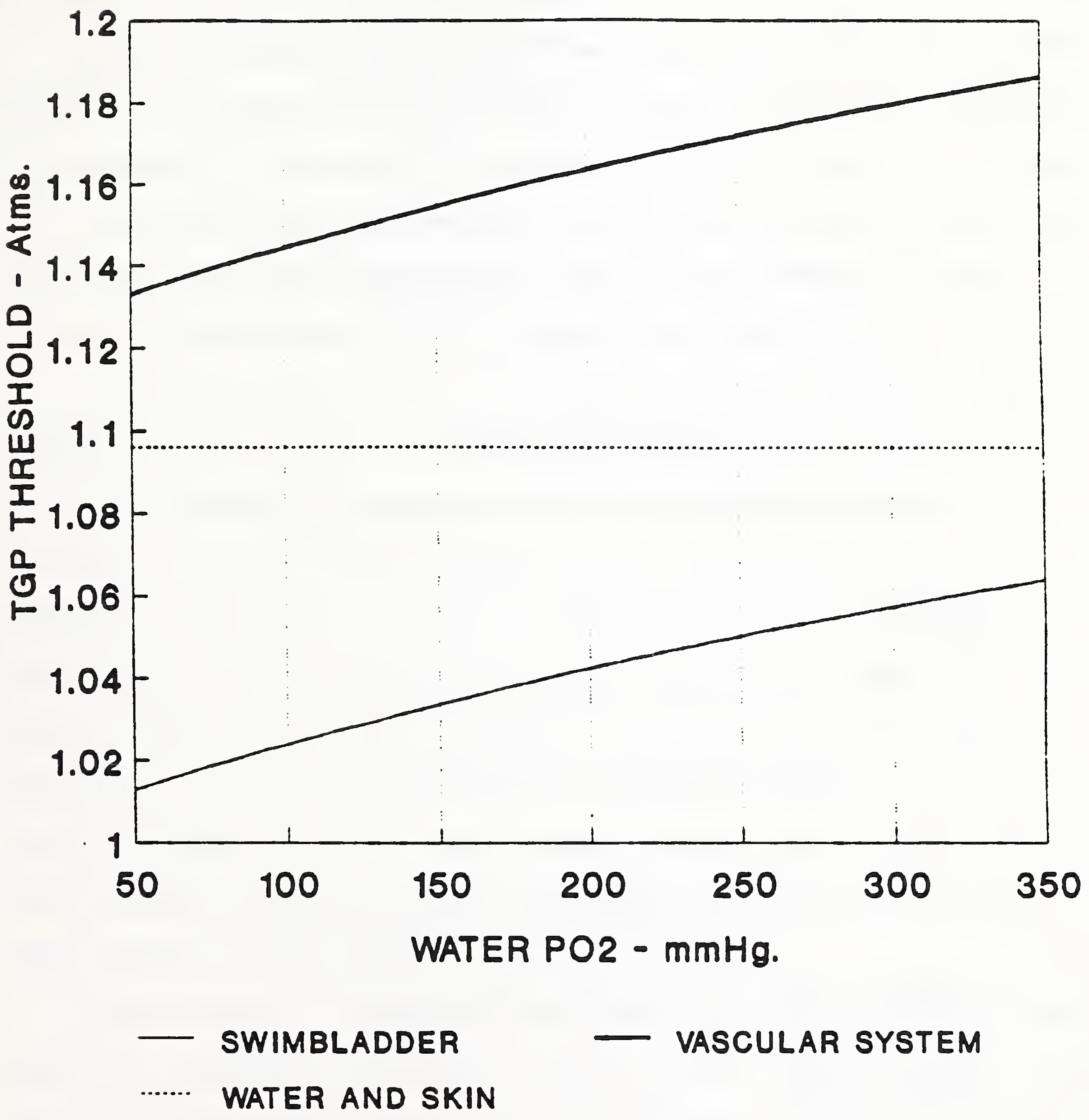


Figure 63. Gas bubble trama TGP thresholds as a function of water pO2 in rainbow trout.

below a water TGP of 1.16 Atmospheres (p02 = 185 mmHg), the time required to incur significant mortalities will be on the order of hundreds of hours with depth and fish size being the primary auxilliary variables. Above a TGP of 1.16 Atmospheres, time to significant mortality will generally be less than 100 h with water p02 and depth being the primary mitigating variables.

Based on these results, the recommended threshold equations that should be applied to the Bighorn river system are as follows.

TGP THRESHOLD EQUATIONS

THRESHOLD CRITERIA FOR CARDIOVASCULAR SYSTEM BUBBLE FORMATION

$$TGP_{CV} = -B + \sqrt{B^2 + C}$$

where: $$B = \frac{1}{2}\left[0.90 \cdot pO2 - \left(P_{atm} + 73.5 \cdot h + 91.33\right)\right]$$

$$C = 1.125 \cdot pO2 \cdot \left(P_{atm} + 73.5 \cdot h + 91.33\right)$$

P_{atm} = Barometric pressure in mmHg.

h = water depth in meters

p02 = partial pressure of dissolved oxygen in mmHg.

THRESHOLD CRITERIA FOR SWIM BLADDER OVERINFLATION

$$TGP_{SB} = -B' + \sqrt{B'^2 + C'}$$

where: $$B' = \frac{1}{2}\left[0.90 \cdot pO2 - \left(P_{atm} + 73.5 \cdot h\right)\right]$$

and $$C' = 1.125 \cdot pO2 \cdot \left(P_{atm} + 73.5 \cdot h\right)$$

THRESHOLD CRITERIA FOR EXTRA-CORPOREAL BUBBLE GROWTH IN GILL LAMELLA AND SUB-DERMAL BLISTERS

$$TGP_{EW} = P_{atm} + 73.5 \cdot h + 75.0$$

Habitat Selection

Introduction

Differences in habitat preference between brown trout and rainbow trout in the Bighorn River may account for the apparent higher incidence of external symptoms of GBT exhibited by brown trout. Habitat preference differences that expose a particular species or age class to high gas supersaturation may also influence relative abundance of these species.

Detection and avoidance of supersaturated water may influence fish survival in waters that contain high levels of dissolved gases. Avoidance can occur by fish sounding or by movement away from supersaturated water (Stevens et al. 1980). Change in hydrostatic pressure associated with an increase in water depth of 1 m reduces gas satruation by 10 % (Gray and Haynes 1977). Weitkamp and Katz (1980) state that it is generally accepted that fish are not able to detect supersaturated water and therefore do not avoid it, although there appear to be exceptions (Bentley et al. 1976; Stickney 1968; Dawley et al. 1976).

Most studies of detection and avoidance of supersaturated waters by salmonids have been conducted with juvenile fish. Lund and Heggerget (1985) found that two-year-old rainbow trout did not avoid supersaturated water at levels from 115 to 125% TGP in tank experiments. Stevens et al. (1980) found that rainbow trout (30 to 45 g) moved laterally to avoid supersaturated water in tank experiments. Heggberget (1984) found that brown trout were less tolerent to supersaturated water than perch (Perca fluviatilis) and eel (Anguilla anguilla) in river cage studies.

Several approachs were used during 1987 to determine if differences in habitat selection exist between brown trout and rainbow trout in the Bighorn River. Macrohabitat use was monitored by snorkeling longitudinal lanes to quantify seasonal trends of trout distribution along the banks and midchannel of the river. Radio transmitters were implanted in 20 trout to determine avoidance behavior and general fish movement. Pressure sensitive radio transmitters designed to detect depth were tested to examine depth selection by trout in relation to changes in gas levels.

Methods

Study Sections for Macrohabitat

Three, 400 m sections were established to observe trout use in relation to stream habitat and cross-river gas levels. Section 1 extended from Rkm 0.5 to 0.9. High nitrogen saturation (mean 118.7 mmHg, range 110.2 - 124.9 mmHg) and high delta P levels (mean 111 mmHg, range 63 - 153 mmHg) were typical for this area. Slightly supersaturated oxygen levels (mean 108.3 mmHg, range 96.9 - 118.8 mmHg) and a slight gradient of decreasing gas levels from the right to left bank occurred. Section 2, located at Rkm 4.5 to 4.9, had lower nitrogen levels (mean 110.3 mmHg, range 100.4 - 121.3 mmHg), higher oxygen levels (mean of 137.3 mmHg, range 101.6 - 135.5 mmHg), lower delta P levels (mean 107 mmHg, range 46 - 188 mmHg), and a less pronounced cross river gradient in gas saturation levels. Section 3 was located at Rkm 9.7 to 10.1. This section was characterized by lower nitrogen levels, higher oxygen and delta P levels, and a lack of a cross river gas gradient compared to uptream sections. Incidence of GBT in brown trout was higher in section 1 than in section 2. Incidence of GBT in rainbow trout was higher in section 2 than in section 1.

Macrohabitat

Three snorkel lanes were monitored from late May to late October in each section (left, middle, and right). Snorkel lanes along the left and right banks were surveyed while maintaining a relatively constant distance from shore of approximately 9 m. These snorkel lanes were chosen to contrast fish distribution in fish in shallow near bank areas and in the deeper midchannel areas. Lanes were swum moving downstream counting the number of brown trout and rainbow trout and the number of each species over 36 cm in length. Data were recorded on underwater slates. All counts were made during day light hours between 9:00 and 17:00. Above-water light levels were determined using a Li-Cor intergrating quantum/radiometer/ photometer.

Radio Telemetry

Pressure sensitive radio transmitters and location transmitters were implanted in 10 brown trout and 8 rainbow trout. Transmitters were designed and built by Custom Telemetry and Consulting (CTC), Athens, Georgia. Pressure sensitive transmitters were temperature compensating and frequencies of both transmitter types were individually identifiable and were in the 30 MHz range in order to operate in the highly conductive Bighorn River water. The eight pressure sensitive transmitters were cylindrical in shape with a mean length of 70.9 mm, a mean diameter of 20.3 mm, and an average weight of 9.6 g in water (Table 36). Mean size of location transmitters was 29 mm long by 16 mm diameter and average weight in water was of 2.5 g (Table 37).

Prior to implantation, pressure sensitive transmitters were operated for 3 d to prevent false calibration due to electronic drift from battery power drain (Haynes 1978). Calibration tests were conducted in Afterbay Reservoir below Yellowtail Dam, where water quality and temperature were the same as in the Bighorn River. Each transmitter was suspended on a metered line at depths of 0, 1, 2, and 3 m and pulse repetitions were measured. Pulse repetition was measured from the leading edge of one pulse to the leading edge of the succeeding pulse. Pulse repetition time decreased with increases in hydrostatic pressure (depth). A linear regression was used to determine the relationship between pulse repetition and depth for each transmitter. To determine depth resolution, unlimited simultaneous discrimination intervals were used (Lieberman et al. 1967). This method accounts for both the uncertainty in the observed pulse rate and the uncertainty in the relationship between pulse repetition and depth. Methods which do not take both uncertainties into account are not appropriate for measurements from precalibrated

Table 36. Specifications of pressure sensitive radio transmitters implanted in brown trout and rainbow trout, August 1987, Bighorn River, Montana (does not include the two proto-type transmitters).

Length (mean)	70.9 mm
Diameter (mean)	20.3 mm
Weight in air	33.6 - 35.0 g
Weight in water	9.3 - 10.0 g
Battery type	3.5 V lithium
Sensor	Cantlever silicon, with pleated stainless steel diaphram
Frequency	30.071 - 30.276 MHz
Theoretical life	28 - 35 d

Table 37. Specifications of location radio transmitters implanted in brown trout and rainbow trout, August 1987, Bighorn River, Montana.

Dimensions (mean)	29 X 16 mm
Weight in air	5.4 - 6.4 g
Weight in water	1.7 - 3.1 g
Battery type	Silver
Frequency	30.043 - 30.237 MHz
Theoretical life	90 d

instruments. Transmitter calibration was done by regressing pulse rate on known depths. Field pulse rates were then converted to confidence intervals for depth using this regression equation, along with estimates of both types of uncertainity. A computer program designed by Milo Adkison and Dan Gustafson (MSU) performed the regression analysis.

After release, radio tagged trout were located and monitored using a 124 cm^2 "loop" antenna and two different receivers. A programable scanning-receiver and pulse counter (Model 2000 Challenger Programable Scanner and Pulse Decoder) manufactured by Advanced Telemetry Systems, Incorporated (ATS), Isanti, Minnesota were used to locate fish. The second receiver and pulse counter, manufactured by CTC (Model CTC-AR-12 and Pulse Counter), were used to record pulse repetition in the field. Transmitter range was approximately 300 m depending on transmitter depth and orientation to receiving antenna. An attempt was made to locate fish daily. Twentyfour hour monitoring of pressure sensitive transmitters was done on two occasions on two different transmitters to assess diurnal trout movements. Fish were also located at night to evaluate night time habitat use. Fish locations were determined by triangualtion and by signal strength. Fish locations were plotted on maps and XY coordinates were used to determine fish locations and movements. A computer program designed by Dan Gustafson (MSU) was used to analyse the data and produce location graphics.

Transmitters were surgically implanted in the abdomens of brown trout and rainbow trout which ranged in weight from 0.29 kg to 1.83 kg and were 29.2 cm to 53.1 cm total length (Tables 38 and 39). We followed the general procedures of Hart and Summerfelt (1975). Fish were collected by electrofishing within the upper 4 km of the river. Fish were anesthetized (MS-222) and were inverted for surgery so that gills were submerged in anesthetic solution. Fish were tagged with a bright orange anchor tag (Floy Tag Company) behind the dorsal fin for identification. A curved cutting needle with 2-0 synthetic absorbable suture (Ethicon J-4534) was used to close incisions. Two to three subcutaneous stitches and four to six exterior stitches were used. Erythromycin (Erythro-200, 25 mg/1 kg) was injected into the dorsal sinus and tetracycline (Polyotic) was applied to the incision to reduce possible infection. Transmitter weight in water did not exceed 1.25% of trout weight out of water as recommended by Winter et al. (1978). Radio tagged trout were held for less than 20 hours before release. Trout were released at the same location from which thet were captured.

Four of the eight pressure sensitive transmitters implanted into trout in August were recovered after 21 d and were recalibrated to determine if elctronic drift had occurred. The approach used for pre-implant calibration was repeated.

Modifications of flow patterns through Afterbay Dam were used to manipulate gas levels and examine behavior of trout when exposed to various levels of supersaturated water. Fish were released when sluice gates were closed for repairs. High gas

Table 38. Length and weight of brown trout and rainbow trout implanted with pressure sensitive radio transmitters, August 1987, Bighorn River, Montana.

Transmitter frequency (MHz)	Trout species[a]	Total length (cm)	Weight (kg)	Transmitter weight in water (g)	Percent of trout weight[b]
30.071	Brown	51.3	1.09	10.0	0.92
30.088	Rainbow	50.8	1.31	9.6	0.73
30.097	Rainbow	52.6	1.83	9.5	0.52
30.110	Brown	51.8	0.99	9.3	0.94
30.125	Brown	51.1	1.00	9.8	1.00
30.138	Brown	53.1	1.72	9.3	0.54
30.258	Rainbow	46.2	1.13	9.5	0.84
30.276	Rainbow	44.7	0.98	10.0	1.02

[a] Brown - *Salmo trutta*, Rainbow - *Salmo gairdneri*.

[b] The transmitter weight in water as a percentage of the trout weight.

Table 39. Length and weight of brown trout and rainbow trout implanted with location radio transmitters, August 1987, Bighorn River, Montana.

Transmitter frequency (MHz)	Trout species[a]	Total length (cm)	Weight (kg)	Transmitter weight in water (g)	Percent of trout weight[b]
30.043	Rainbow	42.2	0.79	2.5	0.003
30.062	Brown	31.8	0.46	2.4	0.005
30.065	Brown	45.5	0.83	2.7	0.003
30.168	Brown	31.2	0.35	1.7	0.005
30.188	Rainbow	47.8	1.03	2.7	0.003
30.196	Rainbow	47.2	0.93	3.1	0.003
30.207	Rainbow	29.2	0.29	2.5	0.009
30.215	Brown	45.7	0.91	2.4	0.003
30.227	Brown	44.7	0.78	2.3	0.003
30.237	Brown	42.2	0.61	2.8	0.005

[a] Brown - *Salmo trutta*, Rainbow - *Salmo gairdneri*.

[b] The transmitter weight in water as a percentage of the trout weight.

levels were created by passing all flow through sluice gates.

Three periods with different dissolved gas levels were created by modification of flow through Afterbay dam during radio-tracking. Gas measurements were taken at the satellite station at Rkm 0.6. Period 1 (all flow over radial gates, Day 1-12) was characterized by delta P values of approximately 90 mmHg and a small amount of day-to-day variation (Figure 64). Period 2 (all flow through sluice gates, Day 12-18) had mean delta P levels of approximately 140 mmHg with a small daily variation (Figure 64). Period 3 (normal operation with both radial gates and sluice gates used, Day 18-38) had an average delta P of 95 mmHg which was slightly greater than period 1 but with a very large day-to-day variation (Figure 64). Total gas levels followed the pattern of delta P values (Figure 65). Oxygen values were relatively constant throughout all three periods (Figure 66).

Gas levels and other water quaility parameters were obtained from satellite stations at Rkm 0.6 and Rkm 4.8. Eight measurements a day at 3 h intervals were used. Gas levels at section 3 were determined using a Common Sensing tensionometer and Winkler titration. Cross-channel gas differenes were determined at Rkm 0.6 on 12 August and Rkm 4.8 on 13 August using a Common Sensing tensionometer. Above water light levels were determined using a Li-Cor intergrating quantum/radiometer-/photometer.

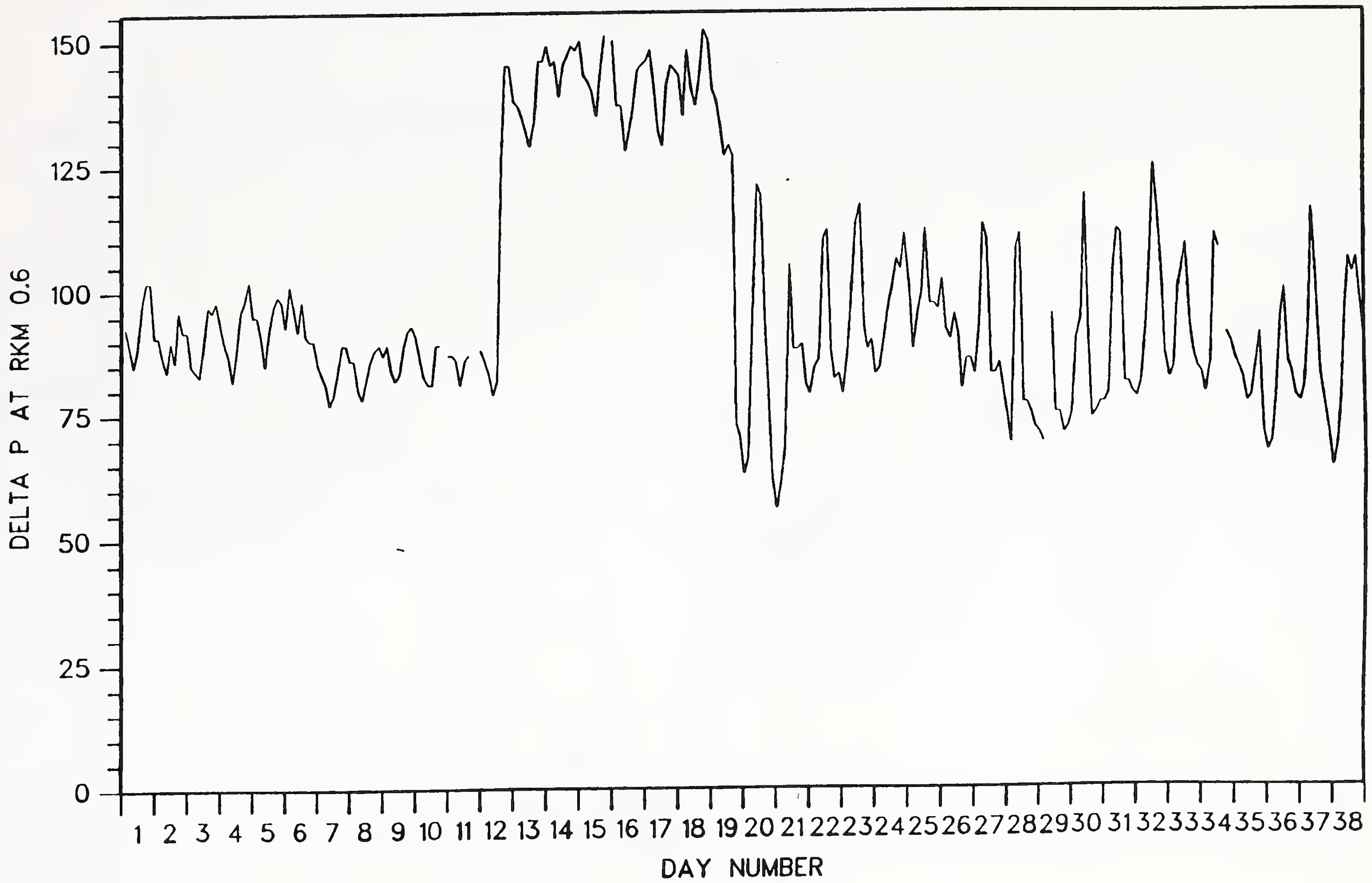


Figure 64. Delta P values (mmHg) measured at satellite station Rkm 0.6 showing three periods of Afterbay Dam operation, Bighorn River, Montana (Day 1 = 6 August 1987).

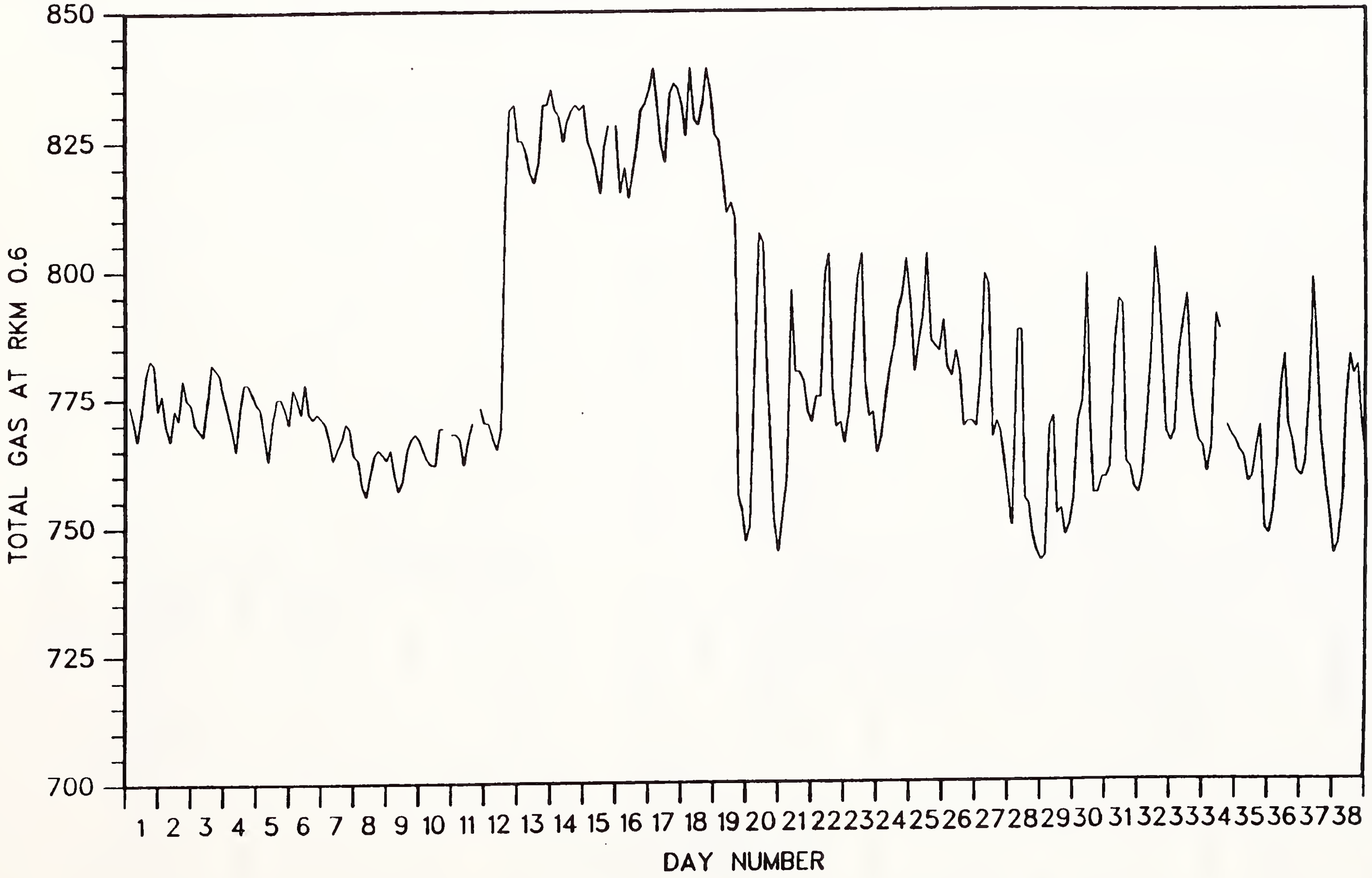


Figure 65. Total gas pressure (mmHg) measured at satellite station Rkm 0.6 showing three periods of Afterbay Dam operation, Bighorn River, Montana (Day 1 = 6 August 1987).

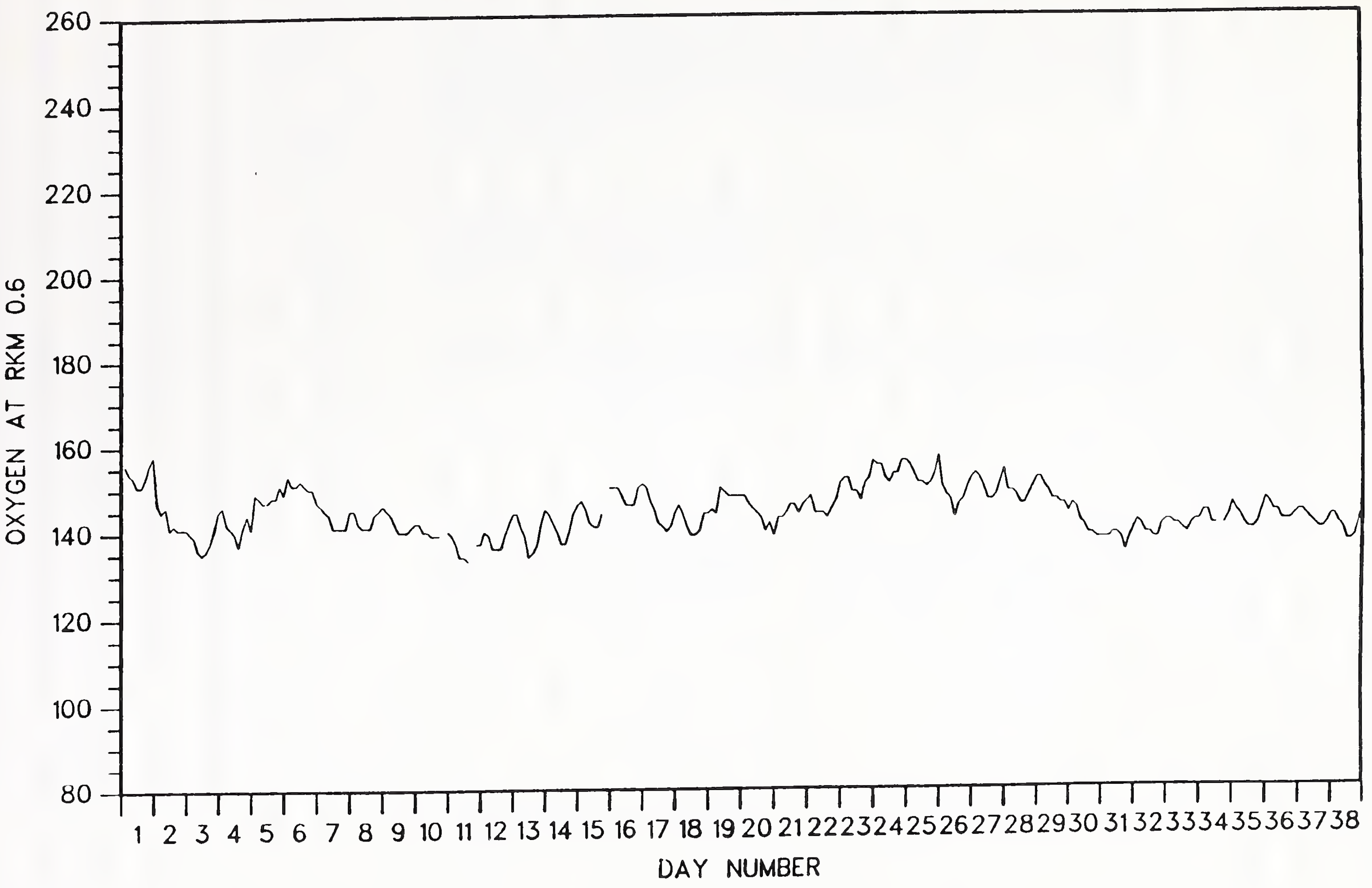


Figure 66. Oxygen pressure (mmHg) measured at satellite station Rkm 0.6 showing three periods of Afterbay Dam operation, Bighorn River, Montana (Day 1 = 6 August 1987).

Results and Discussion

Snorkeling Macrohabitat

Correlation analysis of trout numbers with day number indicated seasonal changes in trout distribution. No correlation existed between above water light levels and trout numbers. Day 1 was 26 May, 1987 and 145 was 17 October. Trout counts for left and right lanes in study sections 1 and 2 were negatively correlated with day number (Table 40). A negative corrlation represents a decrease in trout numbers as the season progresses. Trout counts in the middle lanes were positively correlated with day number for all size categories except rainbow trout longer than 36 cm in section 1. A general pattern of decreasing trout numbers along the near bank lanes and an increase in trout numbers in midchannel from 26 May to 17 October is evident (Figures 67 - 74). Six of the twelve correlations of trout number and day number in each section were significant (Table 40). Section 3 snorkel counts were not evaluated due to poor visibility which reduced reliability of counts and prevented counts after 28 July.

We hypothesize that increased abundance of trout in mid-channel areas during late spring and summer is associated with habitat refuges provided by aquatic vegetation growth. Seasonal changes in aquatic vegetation are dramatic in the Bighorn River. Winter and early spring are characterized by little aquatic vegetation while large amount of vegetation occur in late spring and summer. Because of uniform stream channel shape and the scarcity of low velocity microhabitat locations in the midchannel

Table 40. Correlation analysis of trout abundance in sections 1 and 2 snorkel lane counts with day number (26 May - 17 October 1987), Bighorn River, Montana.

Section	Species	Size	Bank[a]	Correlation coefficient	Significane[b]
1	Brown	<36 cm	LB	-0.50	**
1	Brown	>36 cm	LB	-0.60	**
1	Brown	<36 cm	M	0.46	*
1	Brown	>36 cm	M	0.36	NS
1	Brown	<36 cm	RB	-0.19	NS
1	Brown	>36 cm	Rb	-0.15	NS
1	Rainbow	<36 cm	LB	-0.76	**
1	Rainbow	>36 cm	LB	-0.54	**
1	Rainbow	<36 cm	M	0.63	**
1	Rainbow	>36 cm	M	-0.17	NS
1	Rainbow	<36 cm	RB	-0.06	NS
1	Rainbow	>36 cm	RB	-0.32	NS
2	Brown	<36 cm	LB	-0.60	**
2	Brown	>36 cm	LB	-0.72	**
2	Brown	<36 cm	M	0.09	NS
2	Brown	>36 cm	M	0.04	NS
2	Brown	<36 cm	RB	-0.41	*
2	Brown	>36 cm	RB	-0.51	**
2	Rainbow	<36 cm	LB	-0.35	NS
2	Rainbow	>36 cm	LB	-0.30	NS
2	Rainbow	<36 cm	M	0.46	*
2	Rainbow	>36 cm	M	0.16	NS
2	Rainbow	<36 cm	RB	-0.22	NS
2	Rainbow	>36 cm	RB	-0.50	**

[a] LB - left bank, M - middle, RB - right bank

[b] * $P < 0.05$, ** $P < 0.01$

areas during winter and early spring, we hypothesize that trout concentrate along the banks where river velocities are lower. Maximum velocity theoretically occurs at the surface in the centerline of the channel (Leopold et al. 1964). Near-bank areas in shallow water provide large substrate area per volume of water (compared to the volume of water over an equal size area in

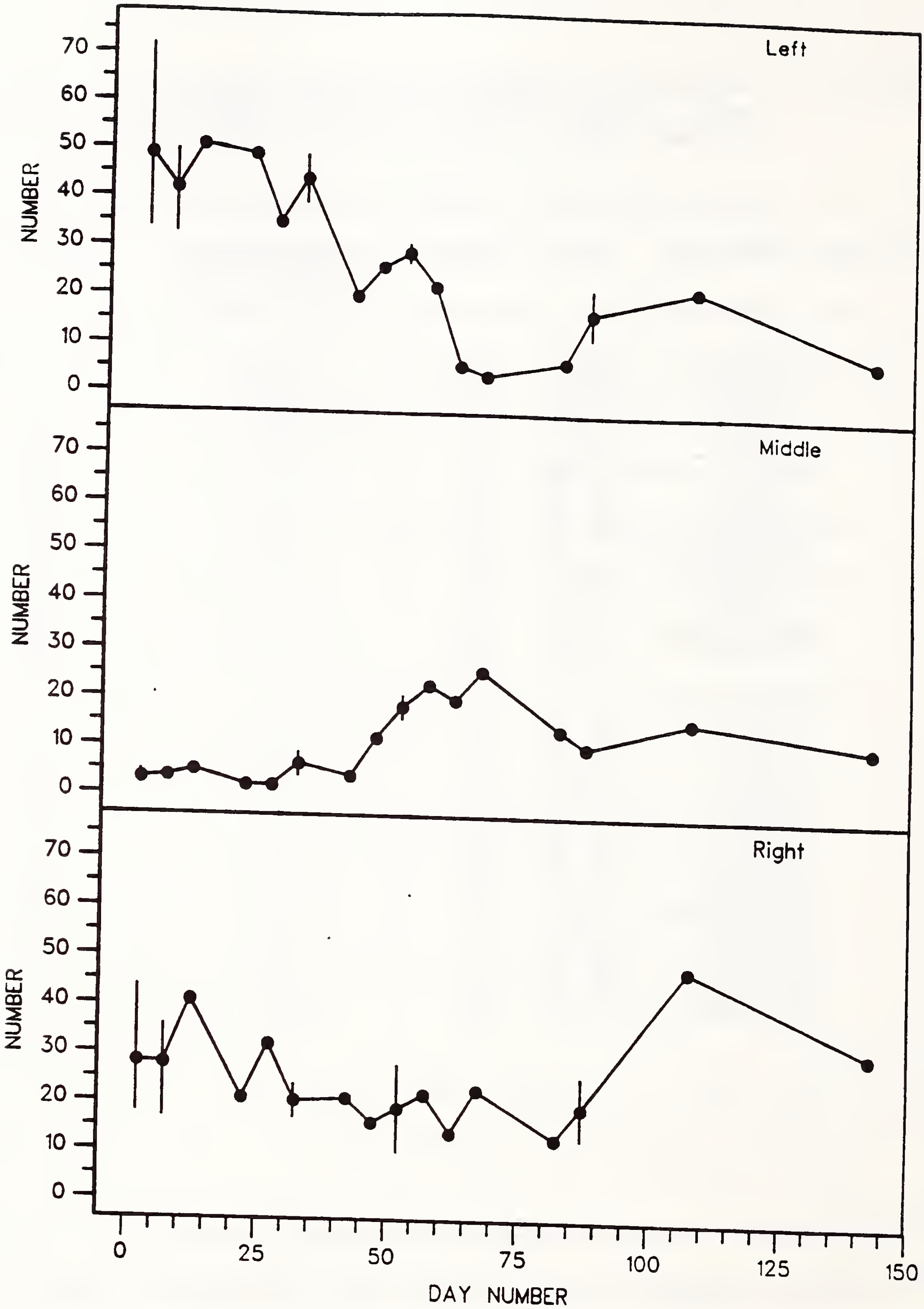


Figure 67. Mean number of brown trout less than 36 cm in length versus day number (26 May - 17 October), section 1, Bighorn River, Montana (points are 5 d averages; bars represent range when more than one count was made within that period).

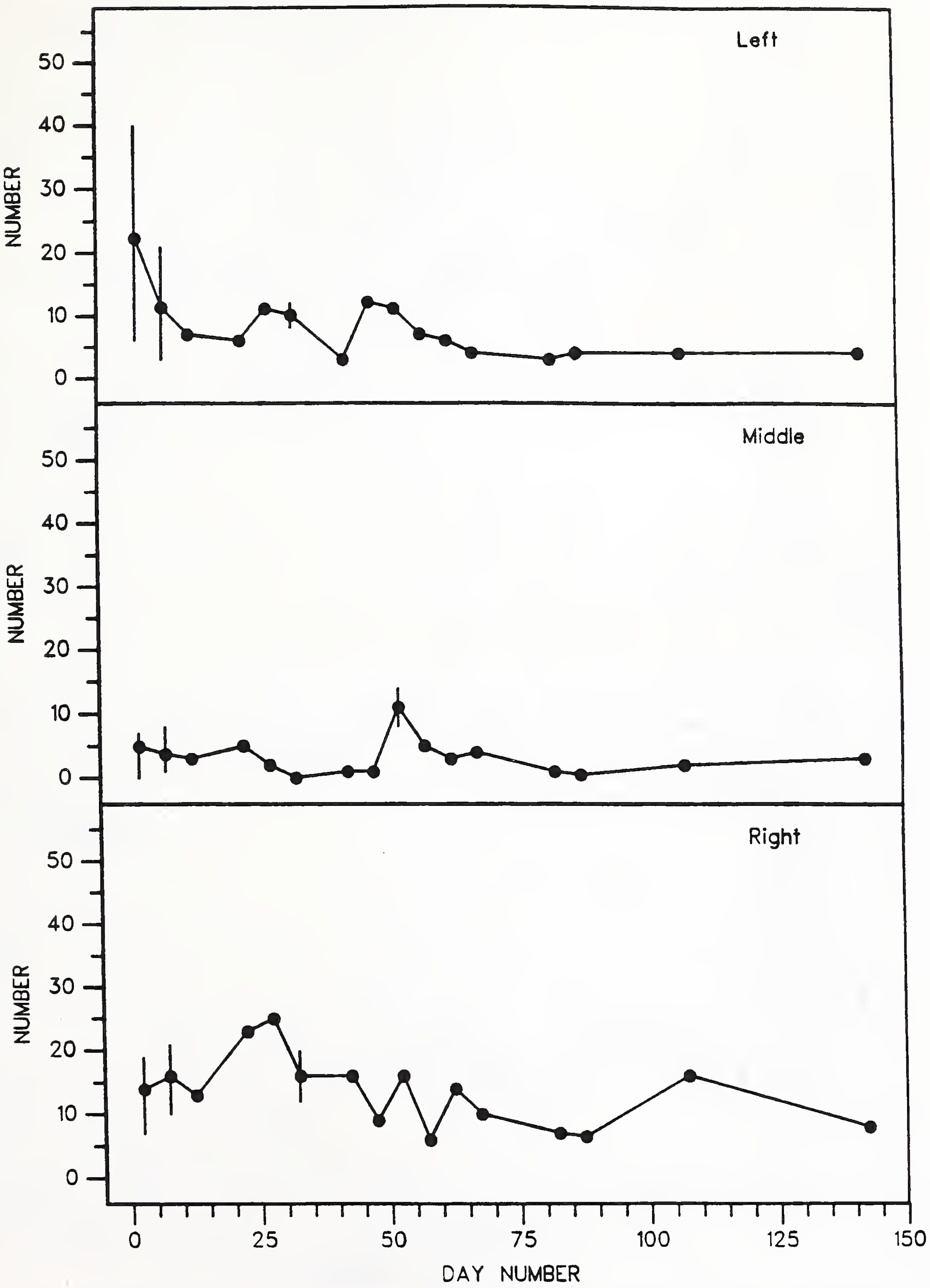


Figure 68. Mean number of brown trout greater than 36 cm in length versus day number (26 May - 17 October), section 1, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

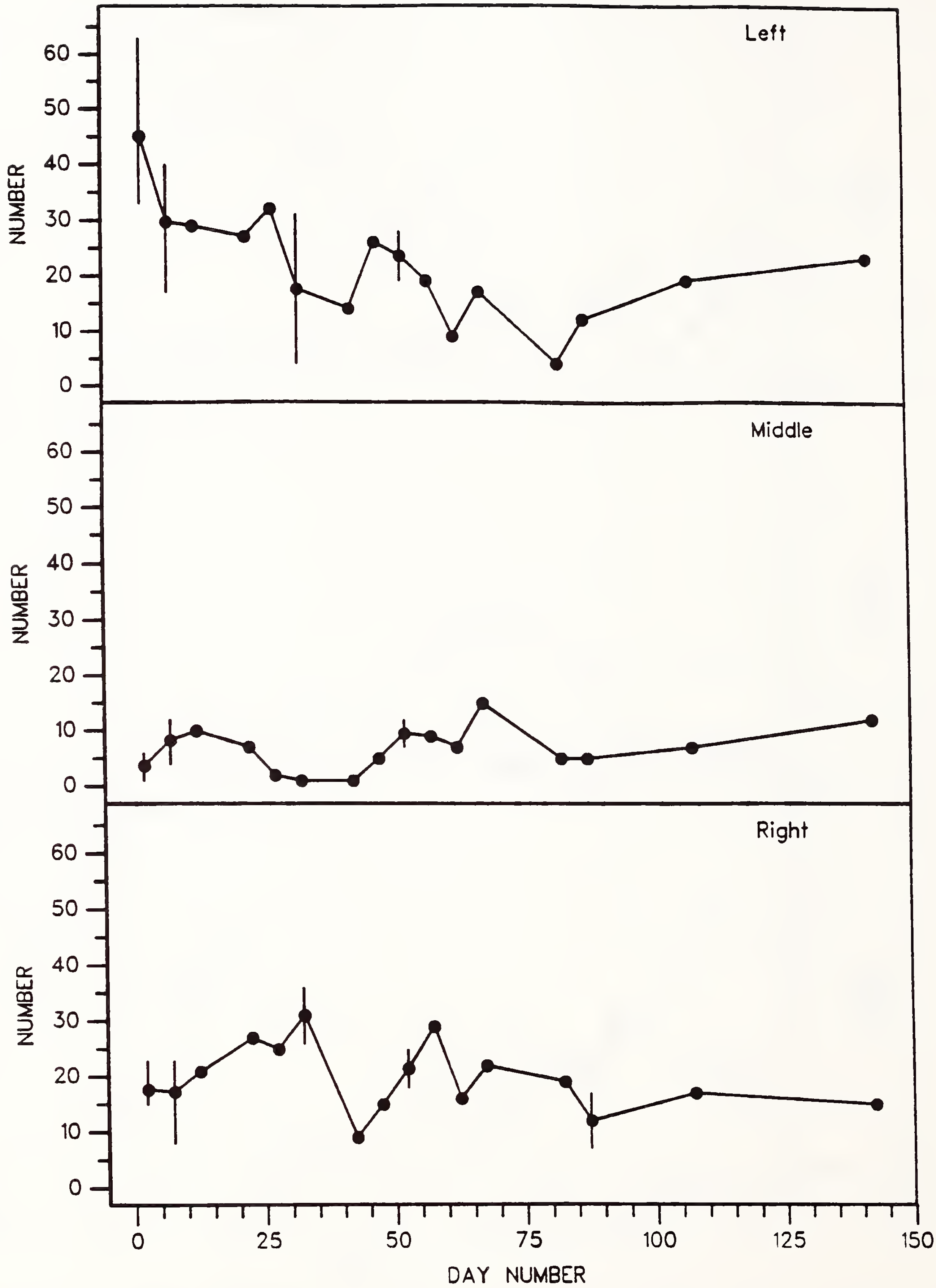


Figure 69. Mean number of rainbow trout less than 36 cm in length versus day number (26 May - 17 October), section 1, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

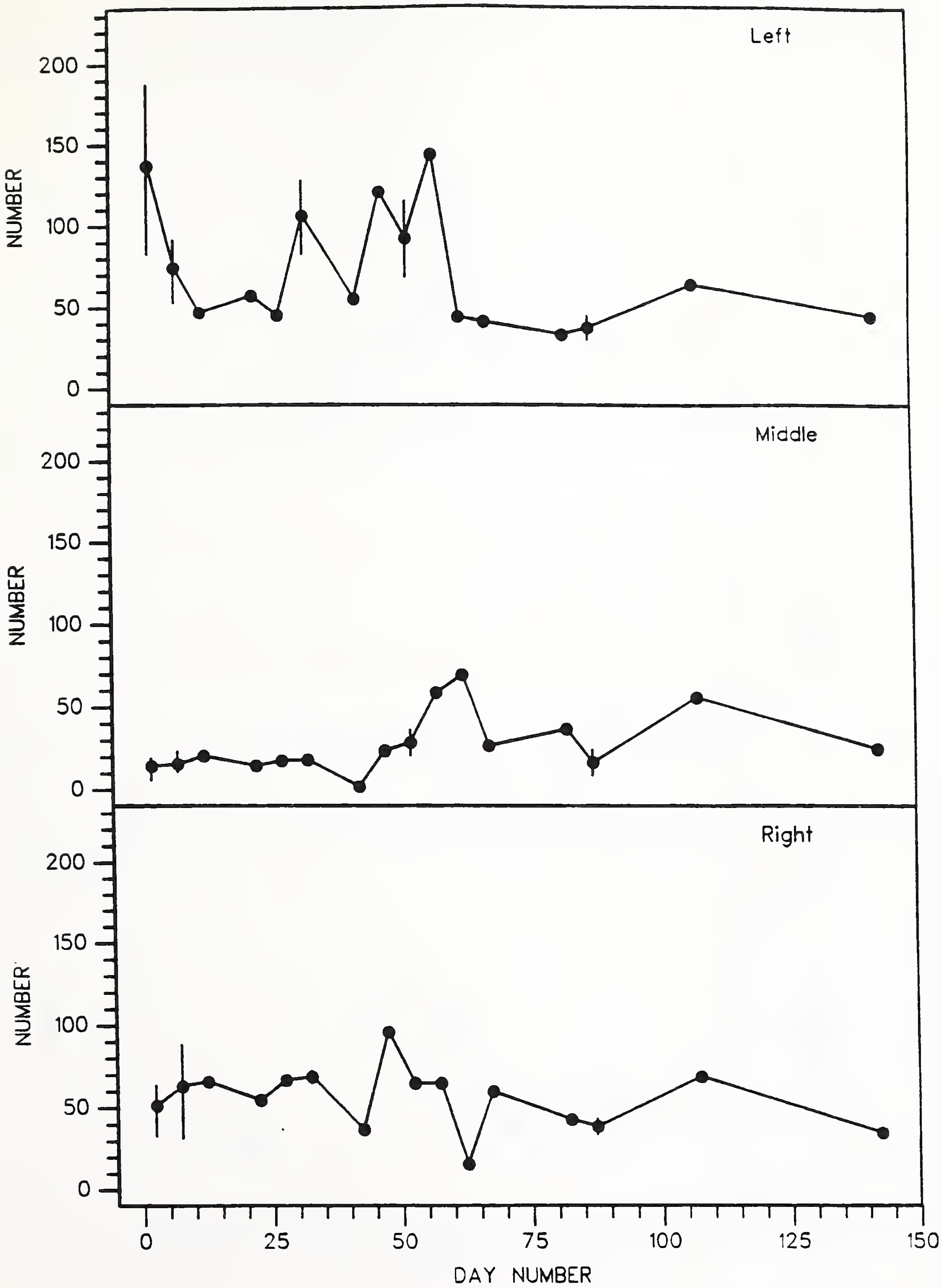


Figure 70. Mean number of rainbow trout greater than 36 cm in length versus day number (26 May - 17 October), section 1, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

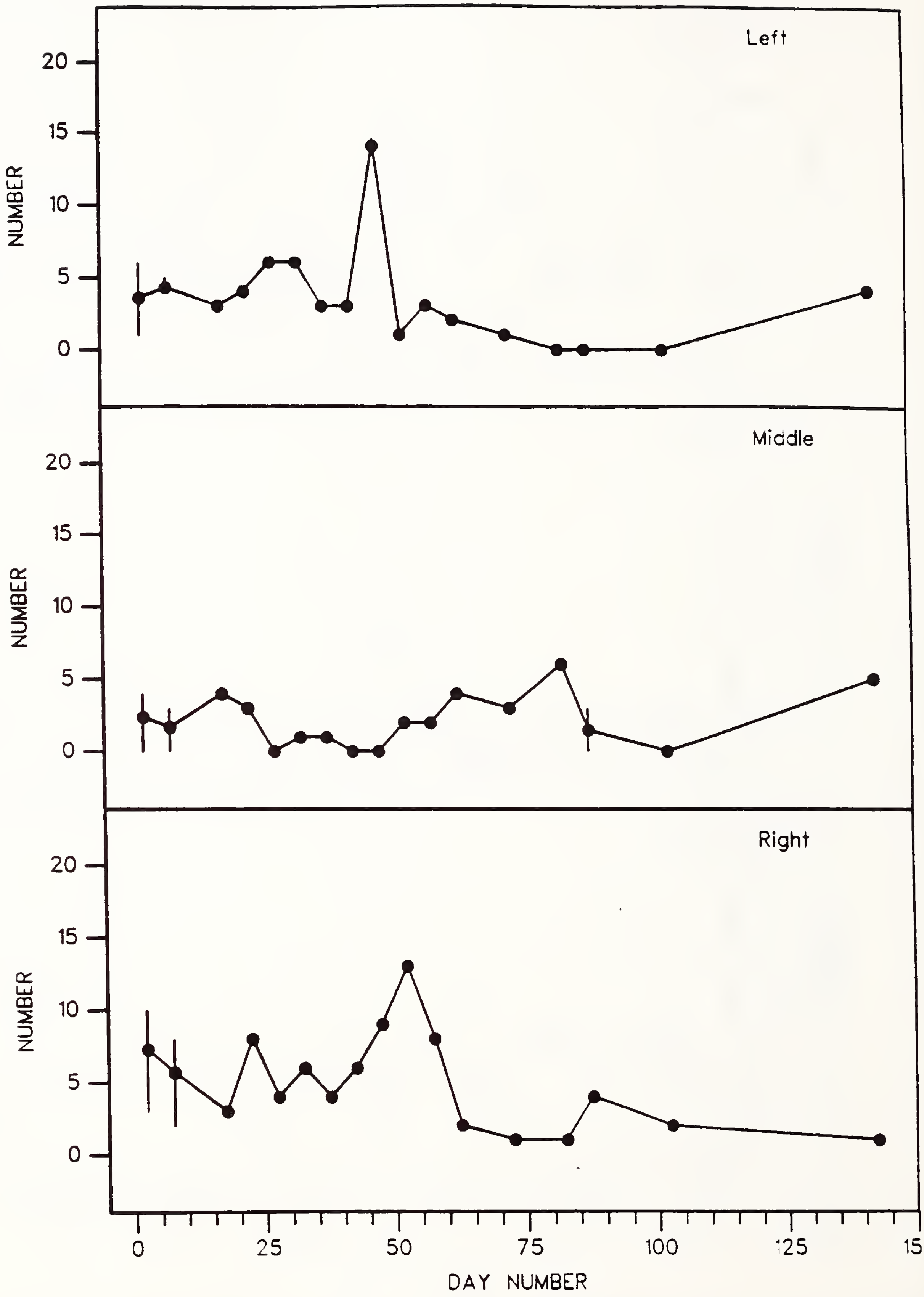


Figure 71. Mean number of brown trout less than 36 cm in length versus day number (26 May - 17 October), section 2, Bighorn River, Montana (points are 5 d averages; bars represent range when more than one count was made within that period).

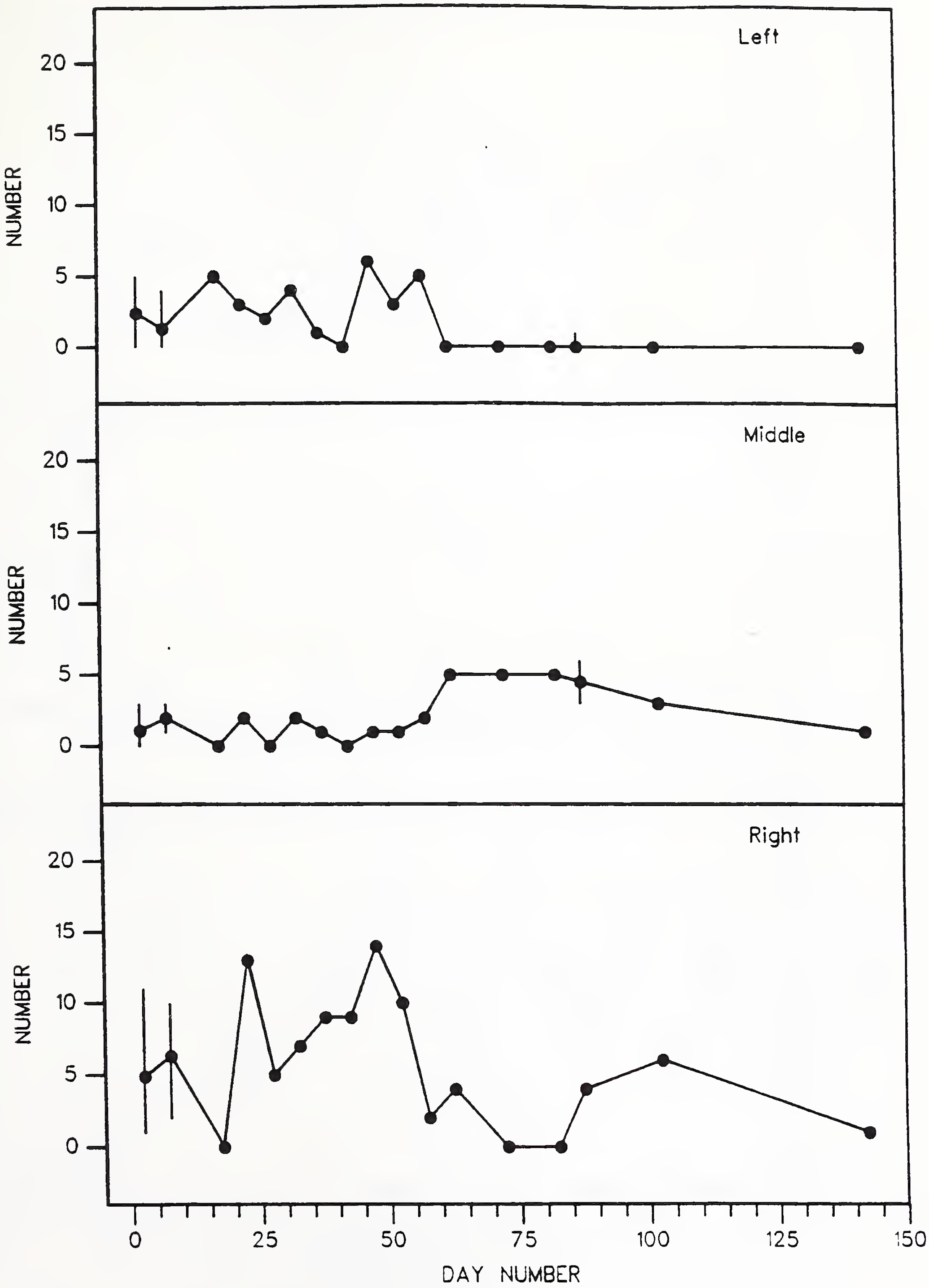


Figure 72. Mean number of brown trout greater than 36 cm in length versus day number (26 May - 17 October), section 2, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

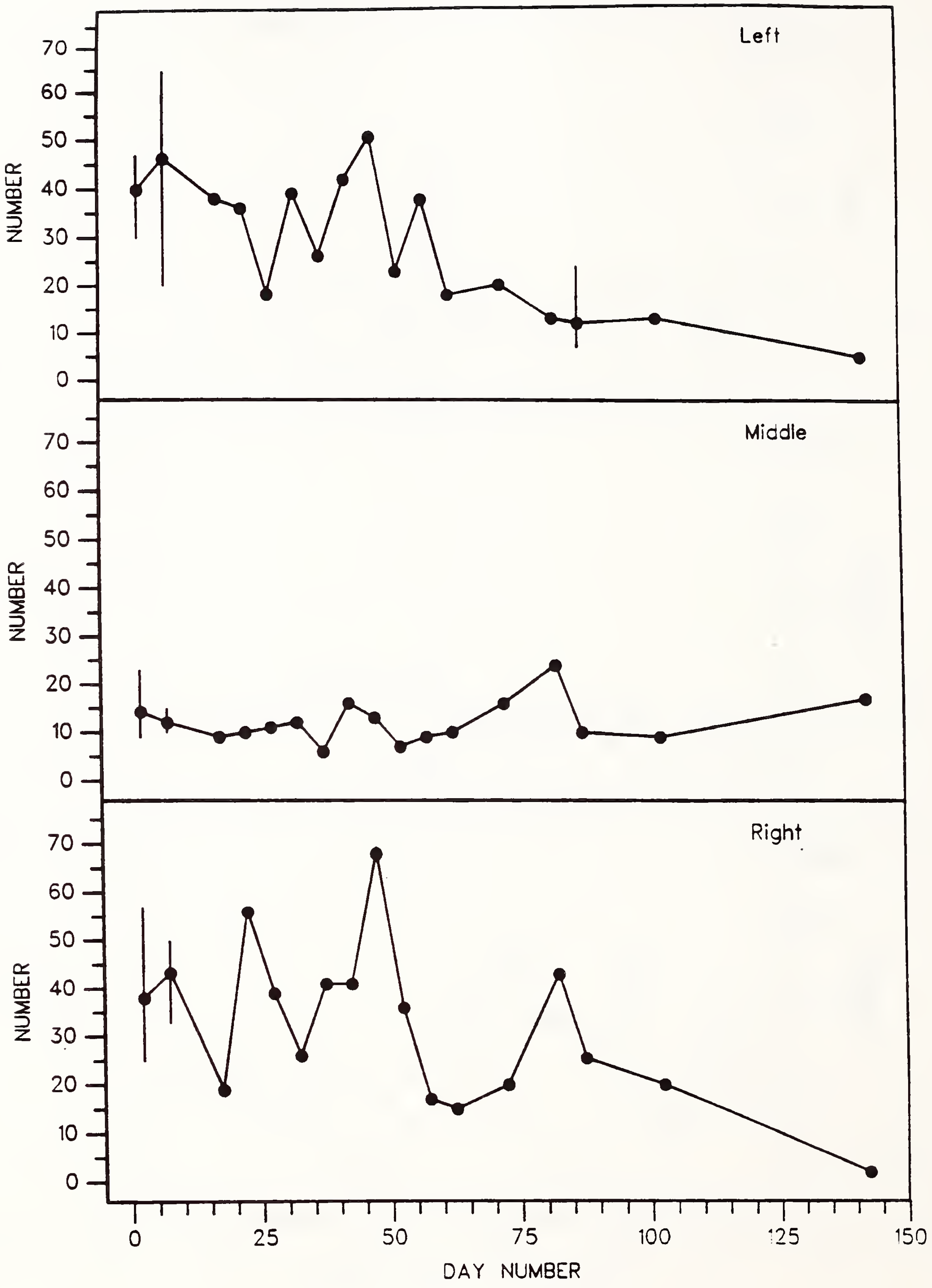


Figure 73. Mean number of rainbow trout less than 36 cm in length versus day number (26 May - 17 October), section 2, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

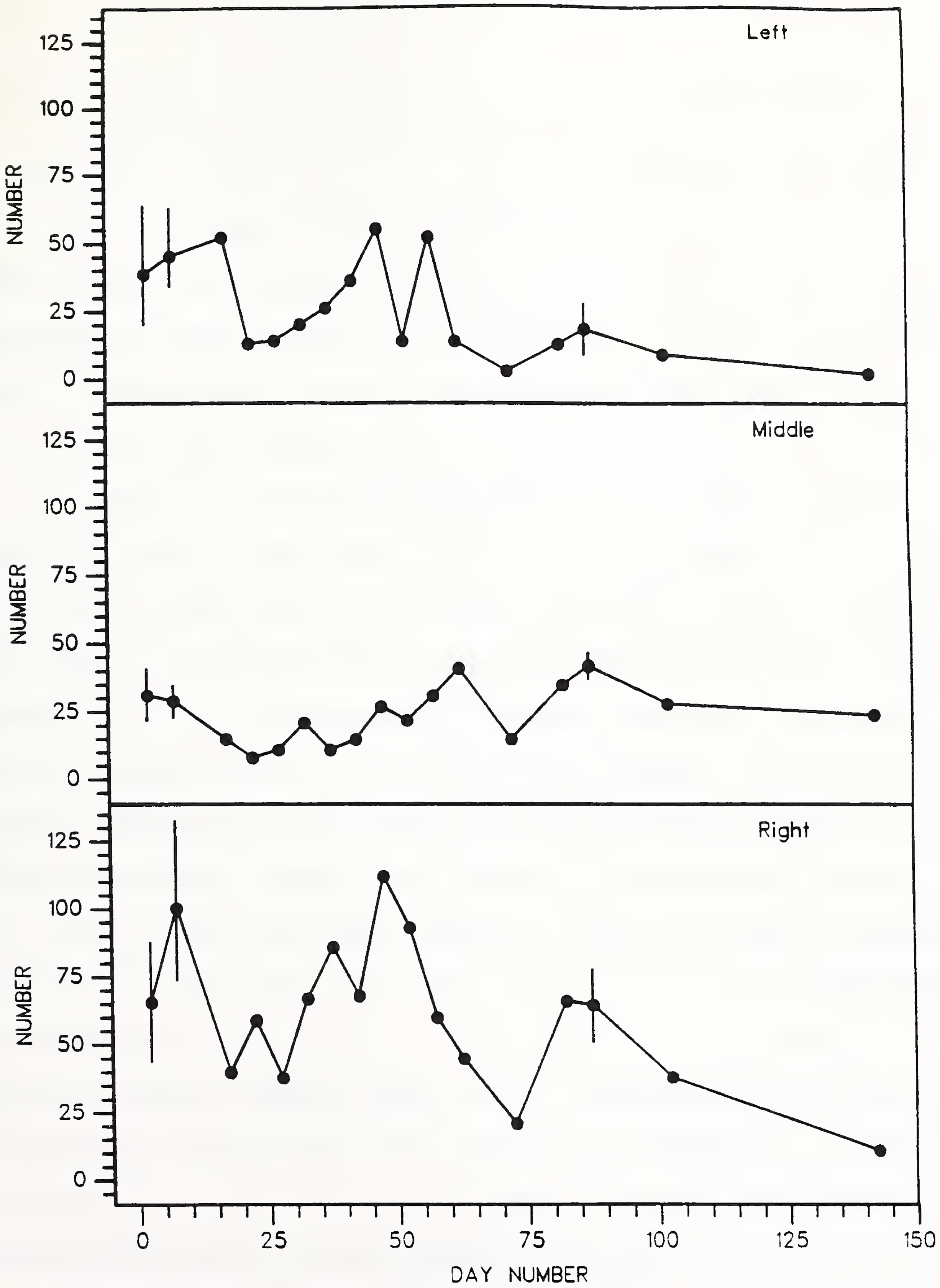


Figure 74. Mean number of rainbow trout greater than 36 cm in length versus day number (26 May - 17 October), section 2, Bighorn River, Montana (points are 5 d averages; bars represent range of counts if more than one count was made within that period).

deeper midchannel area) creating microhabitat locations energetically suitable for trout. As the season progresses (increasing day number), growth of aquatic vegetation may provide reduced velocity areas in midchannel making this habitat more available to trout. Refuge from gas supersaturated water may have been provided during periods of dense vegetation if Bighorn River trout moved in and out of these deeper water areas.

The availablity of midchannel habitat may provide hydrostatic compensation for trout moving in and out of deeper midchannel areas. This may explain the decreased incidence of GBT in trout during late spring and early summer. Trout use deeper water areas and perhaps compensate for high gas levels when sufficient vegetation is present. Shallow depths provide little hydrostatic compensation when trout are concentrated along the banks. The amount and timing of aquatic vegetation growth probably varies from year to year, depending on seasonal conditions.

A change will be made in the snorkel lane sampling method for the 1988 field season. If a distinction between a brown trout and a rainbow trout could not be determined, it was not counted during 1987 snorkeling. This criterion resulted in reduced counts in the middle lanes due to the angle at which fish were observed. Trout along the banks were observed from the side, but those in middle lanes were observed from above, making species determination difficult. Increased vegetation in the middle lanes also made it more difficult to identify species.

During 1988, lanes will be counted using the same method but trout not identifiable to species will be counted.

Pressure Sensitive Transmitter Calibration

The pressure sensitive radio transmitters were ineffective for determining depth selection by trout. Accurate determination of depth was not possible due to insufficient pulse repetition change with changes in depth and to electronic drift. Lack of sufficient change in pulse repetition with depth change resulted in a low calculated regression slope. Since the regression slope is used to interpret depth change, and influences depth resolution of the transmitter (discrimination interval), resolution was not sufficient to accurately measure water depth occupied by radio-tagged trout. Electronic drift, determined by calibrating recovered transmitters, was also large. Since we did not know when drift occurred, resulting data were meaningless. Electronic drift resulted in a change in the relationship between pulse repetition and depth and also reduced the strength of the relationship.

Only one radio tagged rainbow trout (30.088; Table 38) changed position during 24 h and night time monitoring. On 27 August (day 22) at 5:26 trout 30.088 was located moving around the side channel riffle area by island 3 (Figure 75). At 6:20 the trout moved back to its usual position.

The graph illustrating how unlimited simultaneous discrimination intervals are generated (Figure 76) indicates the need for a steeper regression slope for accurate depth

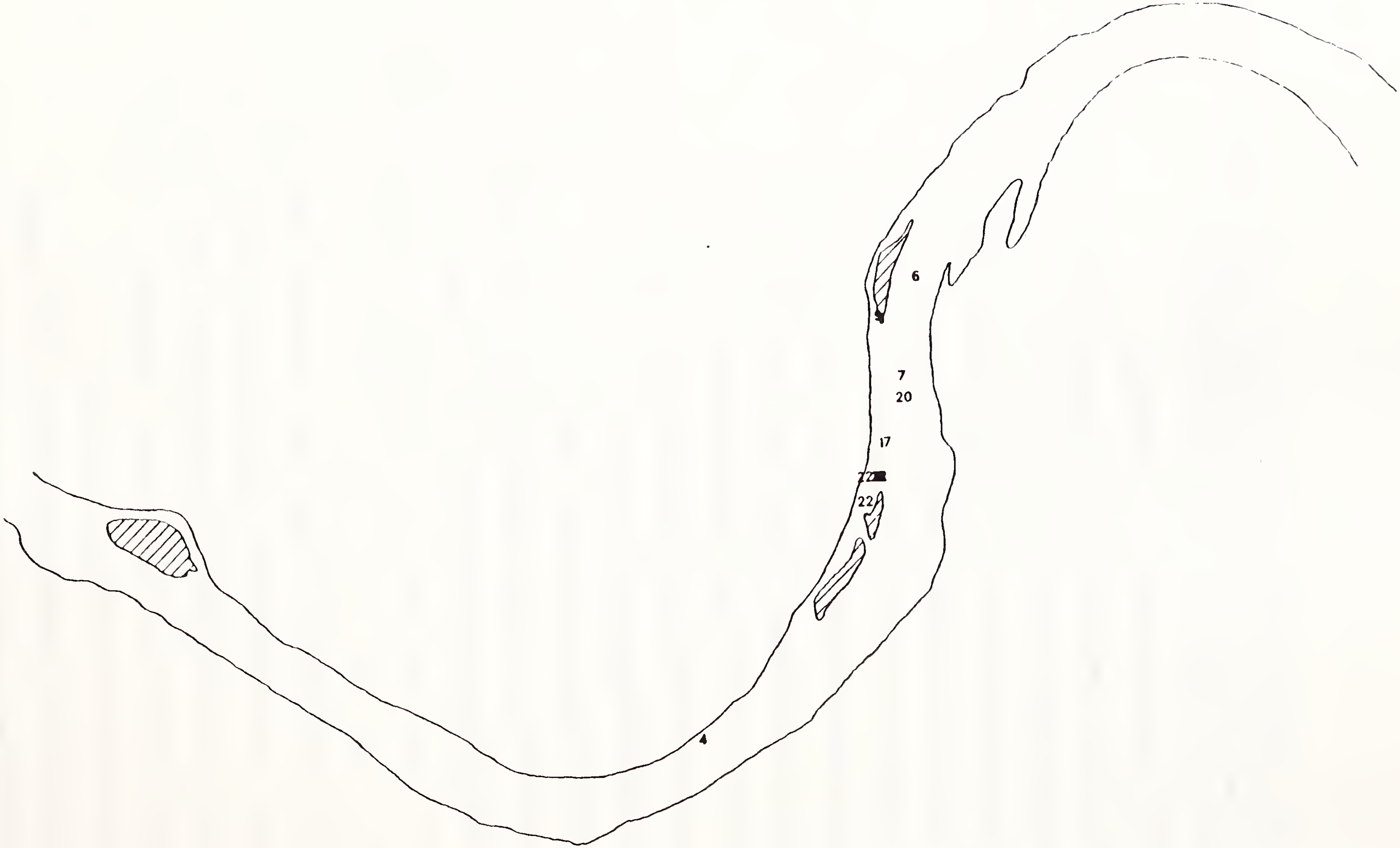


Figure 75. Movement of radio tagged fish 30.088 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

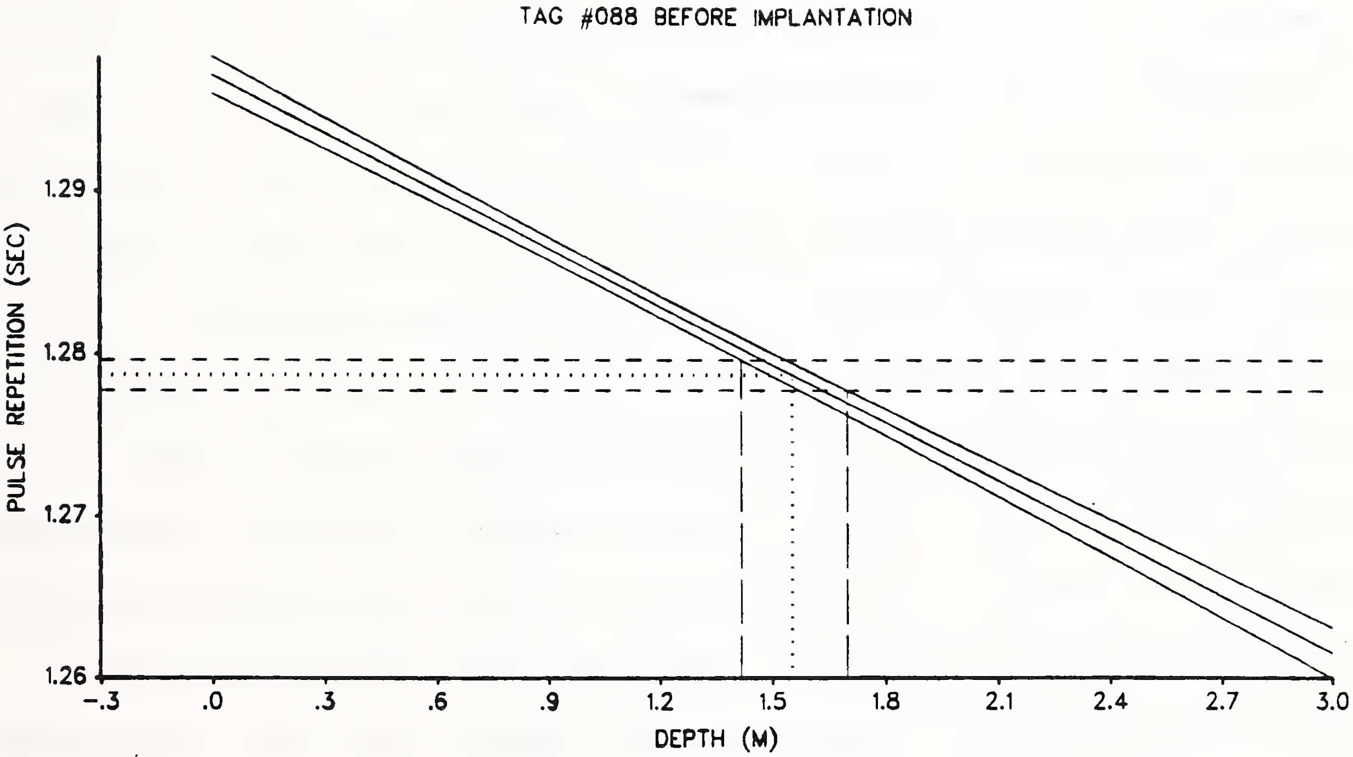


Figure 76. Unlimited simultaneous discrimination intervals for pressure sensitive radio transmitter 30.088 before implantation, Bighorn River, Montana (solid line = regression of pulse repetition on depth, with confidence interval bands; dashed lines = confidence interval for mean Y given observed Y; dotted lines = point estimate of X based on regression; broken lines = discrimination interval for X given Y).

resolution. From the graph, it is apparent that a steeper regression slope (with a high correlation between pulse repetition and depth) would decrease the width of the discrimination interval. A steeper slope can be obtained by increasing the change in pulse repetition with changes in depth.

Another factor contributing to decreased depth resolution was electronic drift. During field operation the relationship between pulse repetition time and depth changed and became weaker. Reduced corrlations between pulse repetition and depth occurred with all four recovered transmitters (Table 41). To determine depth resolution of recovered transmitters that showed electronic drift, the most extreme low and high depth value at a particular pulse repetition from both the pre-implantation calibration and recovery calibration were calculated (Figure 77). The depth resolution of an individual transmitter at any particular pulse repetition decreases with proximity to the mean calibration depth. Because of this, calibration should be done at all experimental depths. The best depth resolution during calibration was 22 cm while the best resolution from a recovered transmitter accounting for electronic drift was 3.02 m.

Fish Movements

Most movement of radio-tagged trout occurred during the first 5 d following release. During the remainder of the monitoring period, little upstream/downstream movement occurred (Figure 78). A high level of initial movement is commonly found when radio tagged trout are released. Average daily movement was

Table 41. Slope and Y-intercept values for regression equations and pulse repetition/depth relationships for pressure sensitive radio transmitters implanted in brown trout and rainbow trout, August 1987, Bighorn River, Montana.

Transmitter frequency	Slope	Y-intercept	Pulse repetition (s) at depth:				r-squared
			0 m	1 m	2 m	3 m	
30.071[a]	0.00083	1.554	1.554	1.555	1.555	1.556	0.6658
30.071[b]	-0.00132	1.539	1.539	1.537	1.536	1.535	0.1801
30.088[a]	-0.01196	1.298	1.298	1.287	1.275	1.263	0.9914
30.097[a]	-0.01612	1.551	1.551	1.535	1.519	1.503	0.9818
30.097[b]	-0.01402	1.528	1.528	1.513	1.498	1.482	0.9438
30.110[a]	-0.01616	1.629	1.629	1.613	1.597	1.581	0.9928
30.125[a]	-0.01274	1.582	1.582	1.569	1.557	1.544	0.9580
30.125[b]	-0.01027	1.526	1.526	1.515	1.505	1.495	0.4044
30.138[a]	-0.00838	1.548	1.548	1.539	1.531	1.523	0.9720
30.258[a]	-0.00917	1.527	1.527	1.518	1.509	1.500	0.9278
30.276[a]	-0.01472	1.551	1.551	1.536	1.521	1.507	0.9729
30.276[b]	-0.01235	1.542	1.542	1.530	1.518	1.505	0.3348

[a] Pre-implant calibration.

[b] Post-implant calibration, only for recovered transmitters.

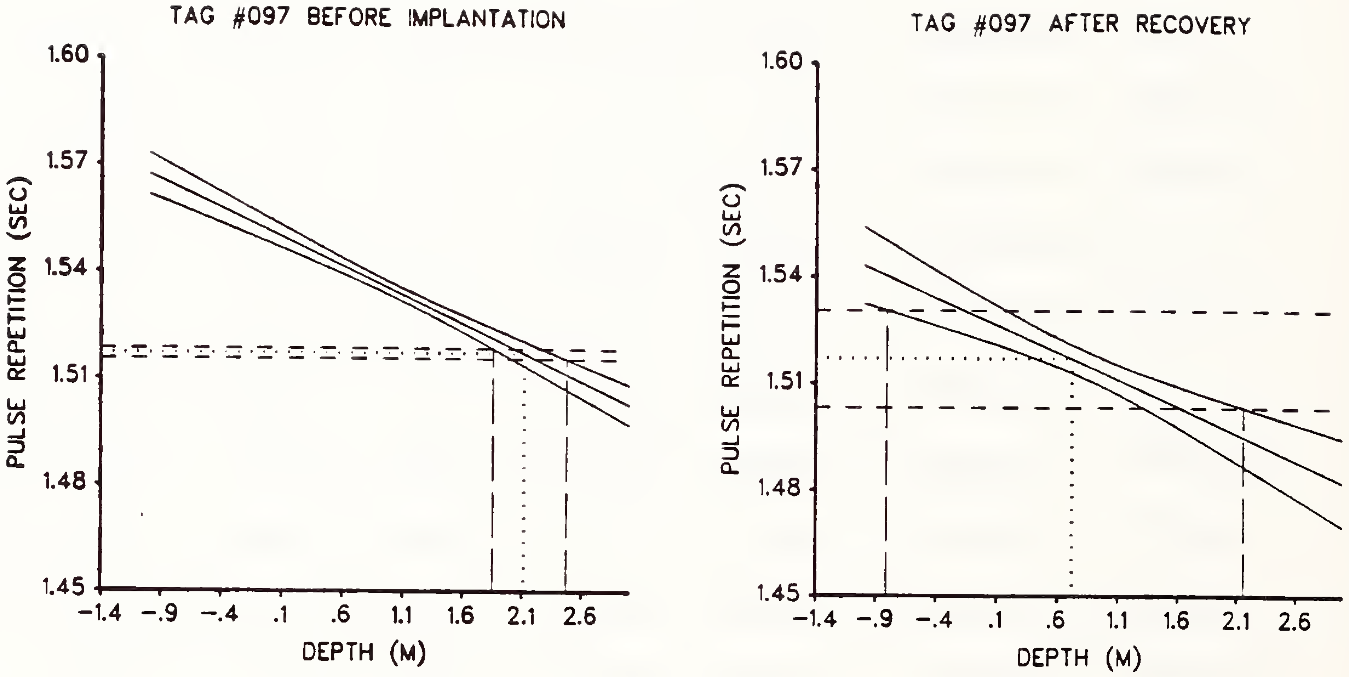


Figure 77. Unlimited simultaneous discrimination intervals for pressure sensitive radio transmitter 30.097 before implantation and after recovery, Bighorn River, Montana (solid line = regression of pulse repetition on depth, with confidence interval bands; dashed lines = confidence interval for mean Y given observed Y; dotted lines = point estimate of X based on regression; broken lines = discrimination interval for X given Y).

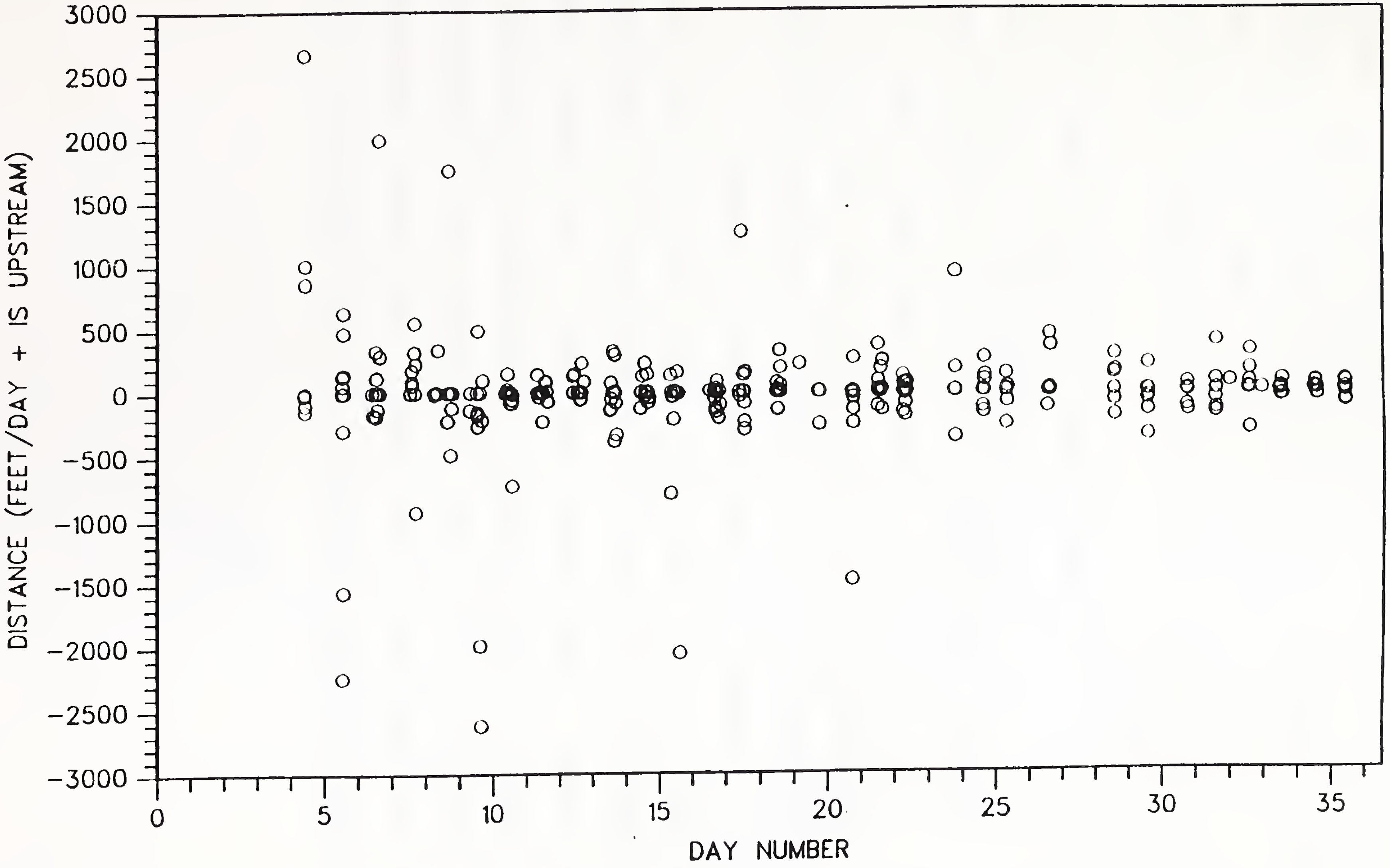


Figure 78. Distance traveled per day by radio tagged trout, August and September 1987, Bighorn River, Montana (each point is an individaul trout; positive distance represents movement upstream, negative distance represents movement downstream).

less than 1 m for the 31 d tagged trout were monitored.

There was no significant difference between brown trout and rainbow trout ($P < 0.01$) in distance traveled per day. There was a significant difference among all radio-tagged trout (ANOVA $P > 0.15$) in distance traveled per day. These data indicate that certain individuals traveled more than others, but it was independent of species.

Pressure sensitive transmitters were either recovered or lost after day 21 which must be considered when interpreting Figure 77. Some of the outliers (points that represent trout that had a high level of daily movement) represent trout implanted with pressure sensitive transmitters. The lack of outliers during period 3 may be a result of removing individual trout having a tendency to move more from the sample.

These data indicate that radio tagged trout did not change their upstream/downstream position in the stream in response to higher gas levels. High diurnal variation in gas levels (Period 3) did not result in trout movement. There was no difference between movements of brown trout and rainbow trout although some individual fish moved more than others. Most trout remained in very localized positions throughout the test (Figures 79 - 91).

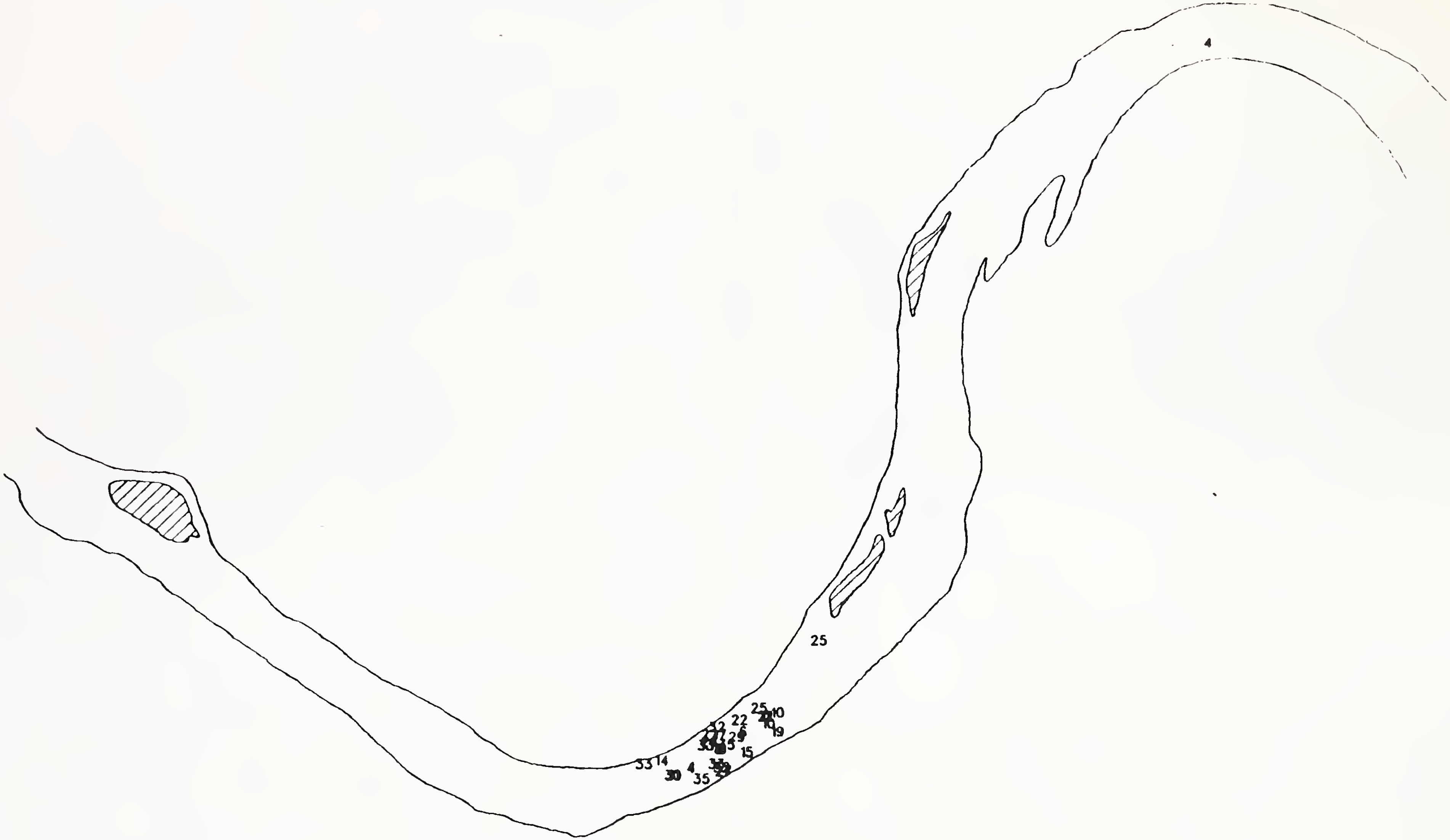


Figure 79. Movement of radio tagged fish 30.043 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

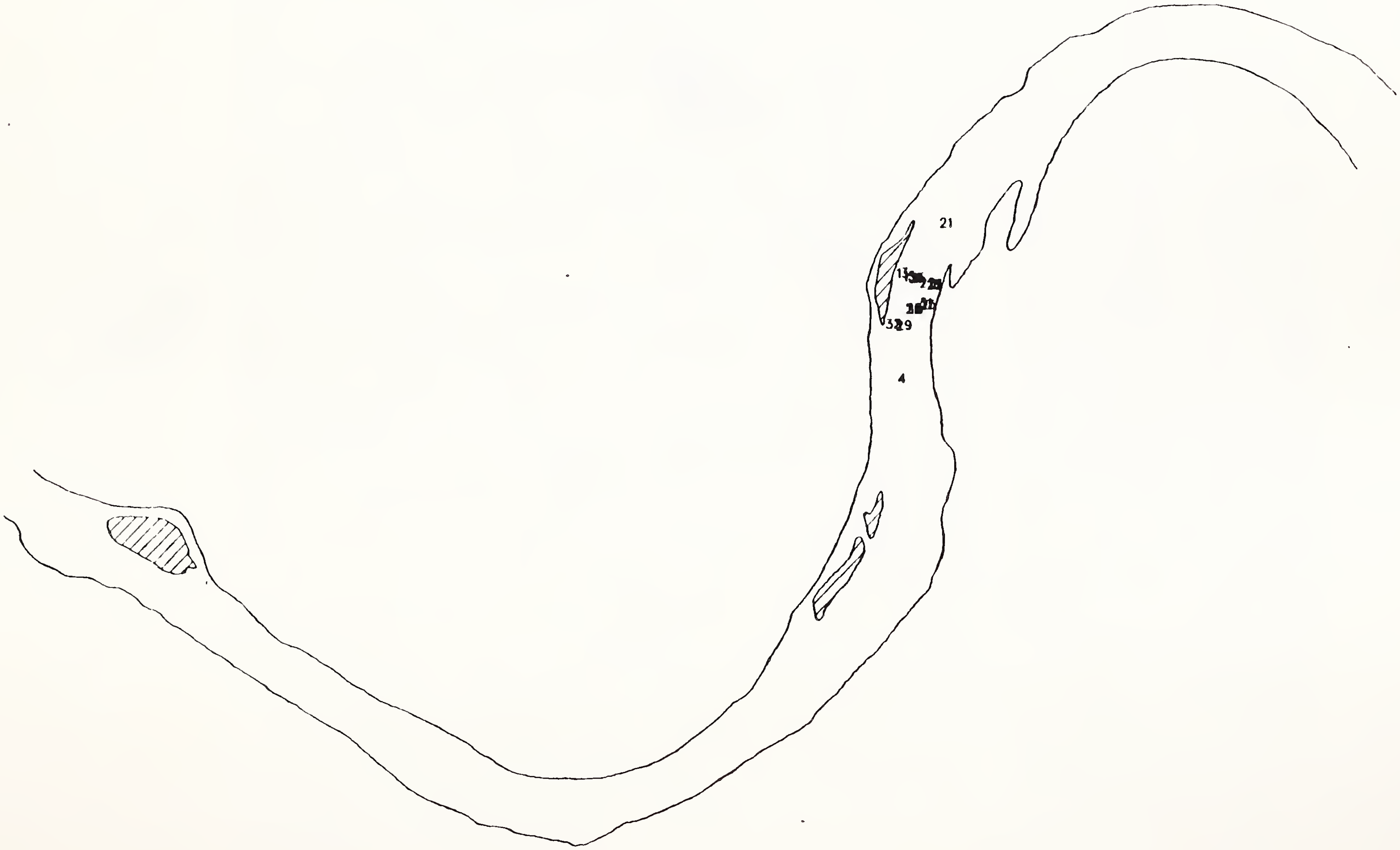


Figure 80. Movement of radio tagged fish 30.062 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

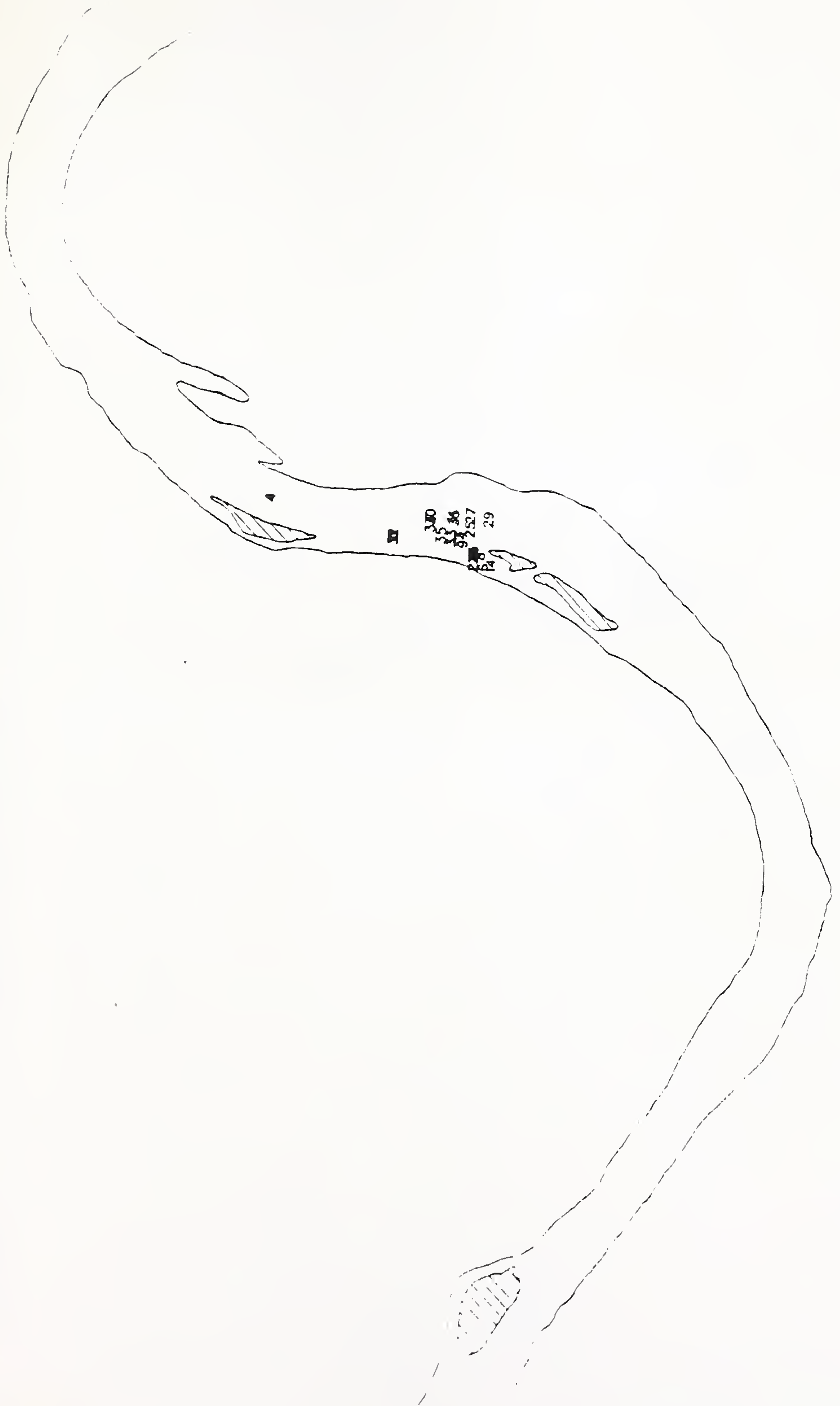


Figure 81. Movement of radio tagged fish 30.065 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

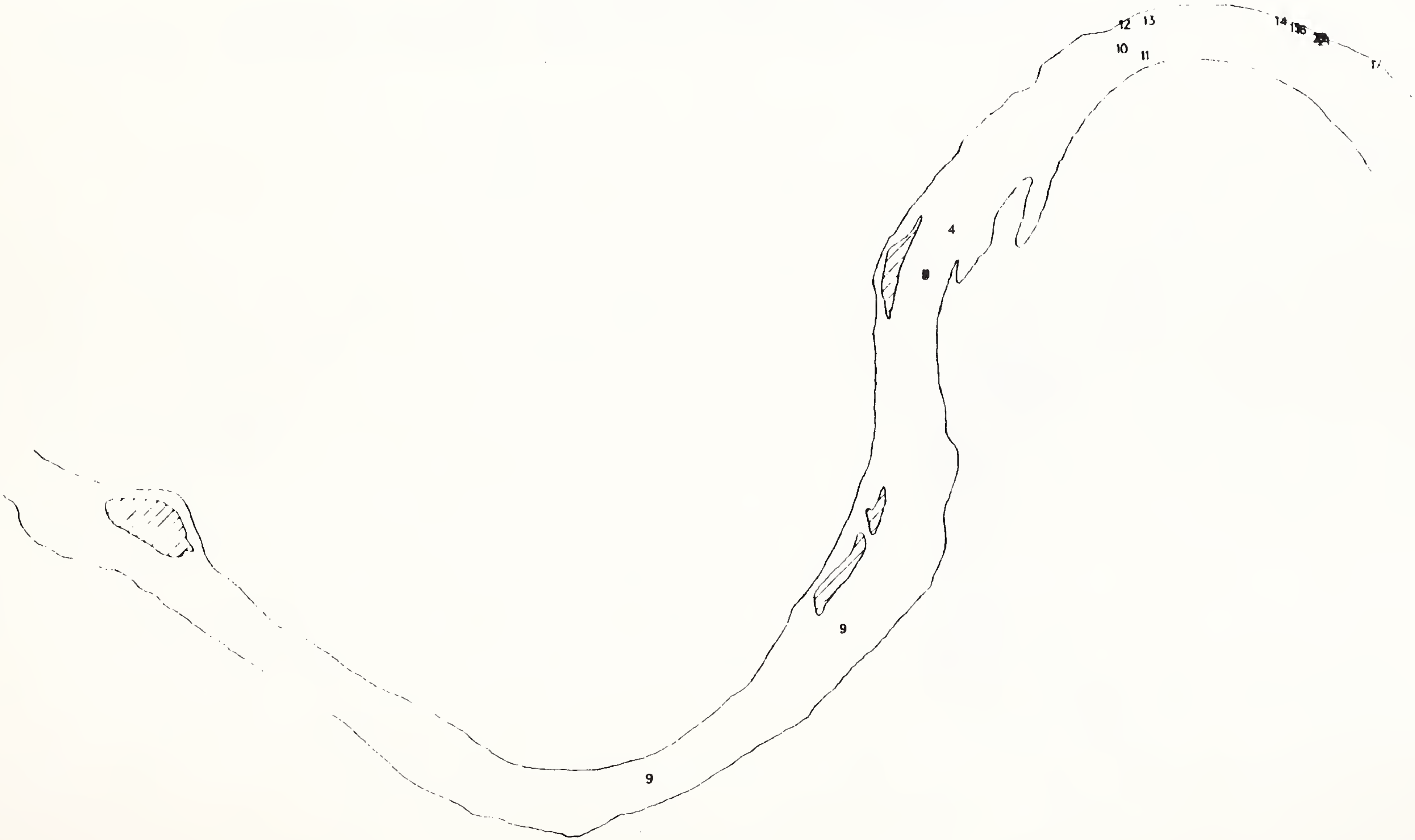


Figure 82. Movement of radio tagged fish 30.071 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

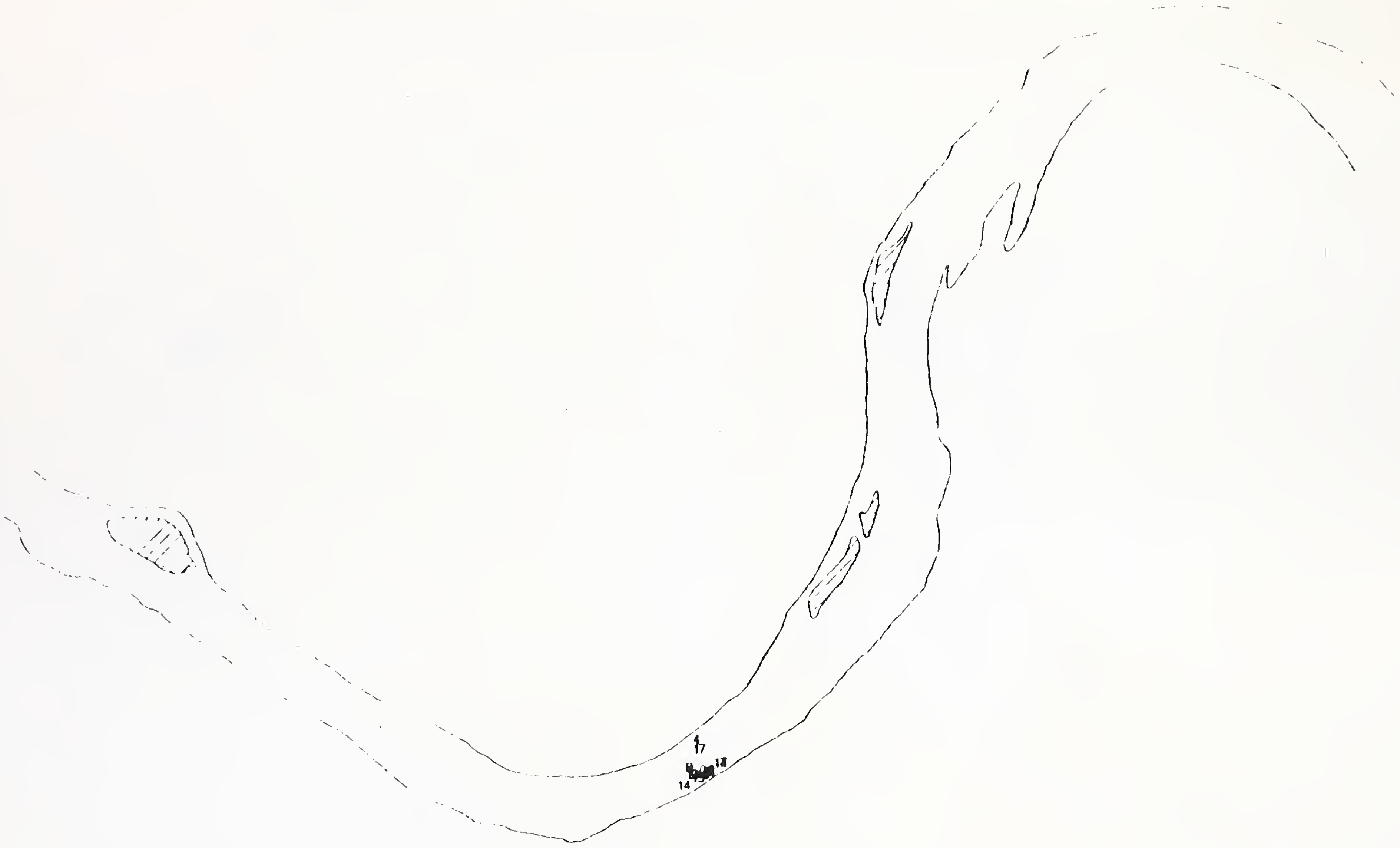


Figure 83. Movement of radio tagged fish 30.097 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

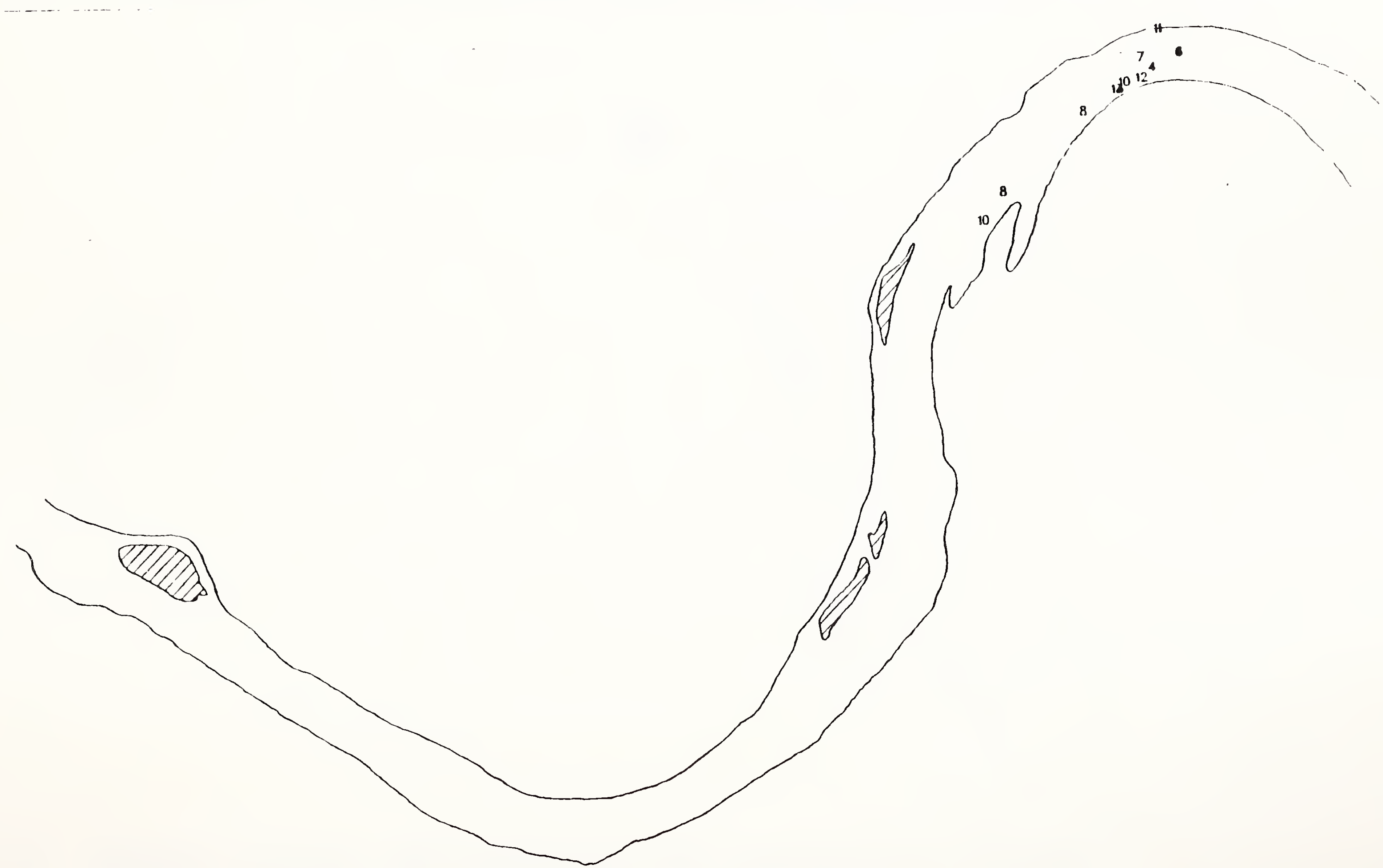


Figure 84. Movement of radio tagged fish 30.110 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

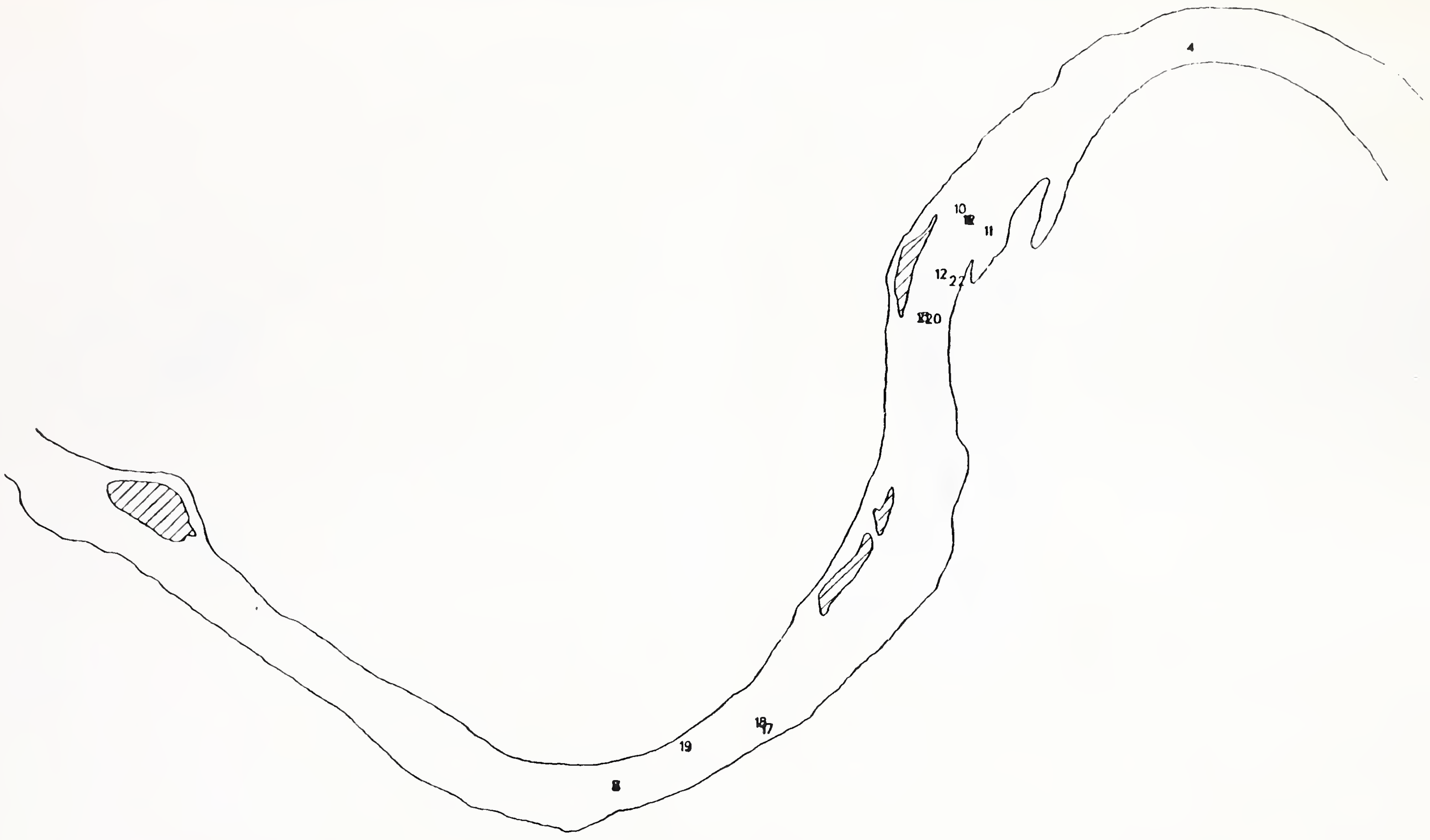


Figure 85. Movement of radio tagged fish 30.125 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

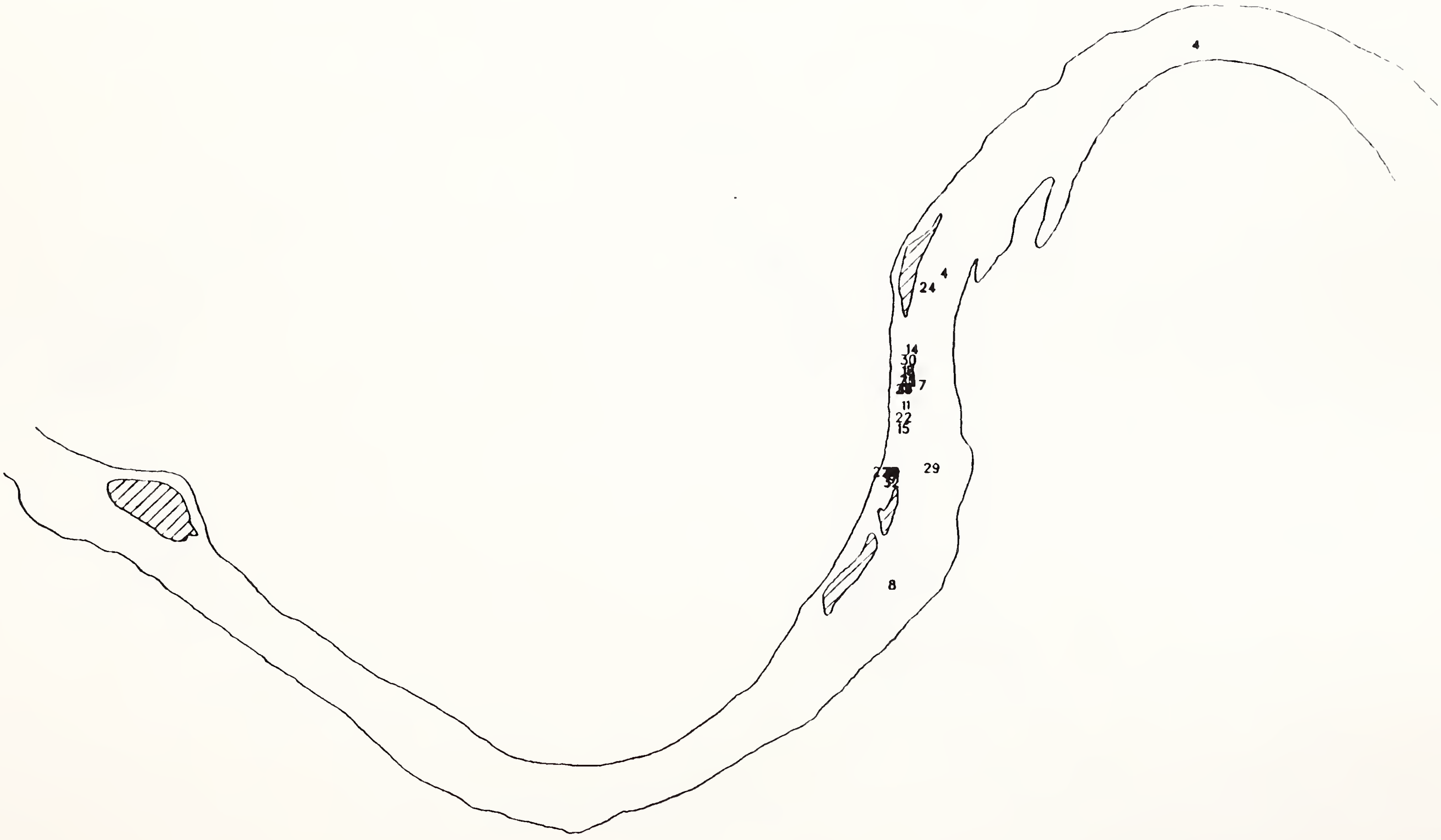


Figure 86. Movement of radio tagged fish 30.168 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

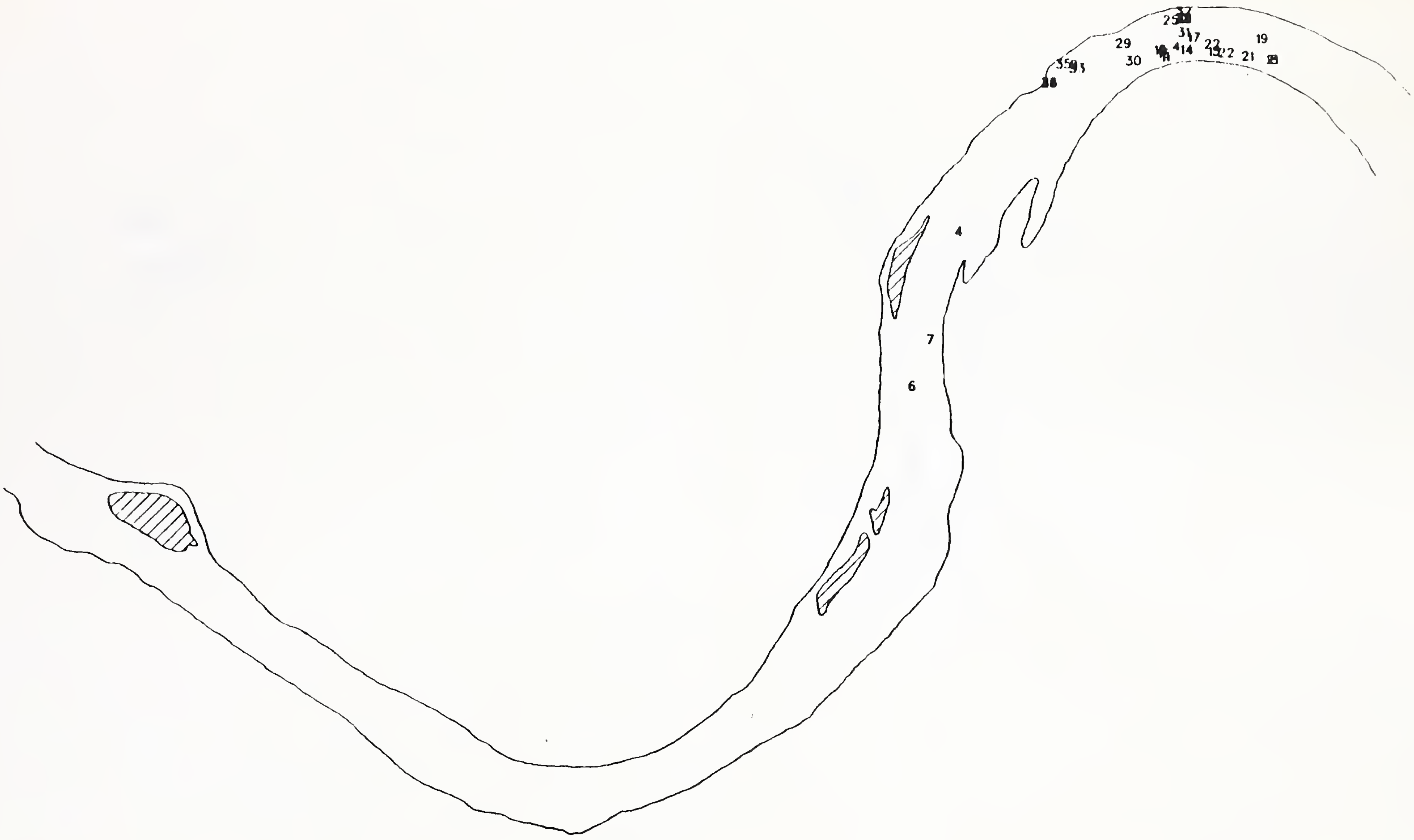


Figure 87. Movement of radio tagged fish 30.188 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

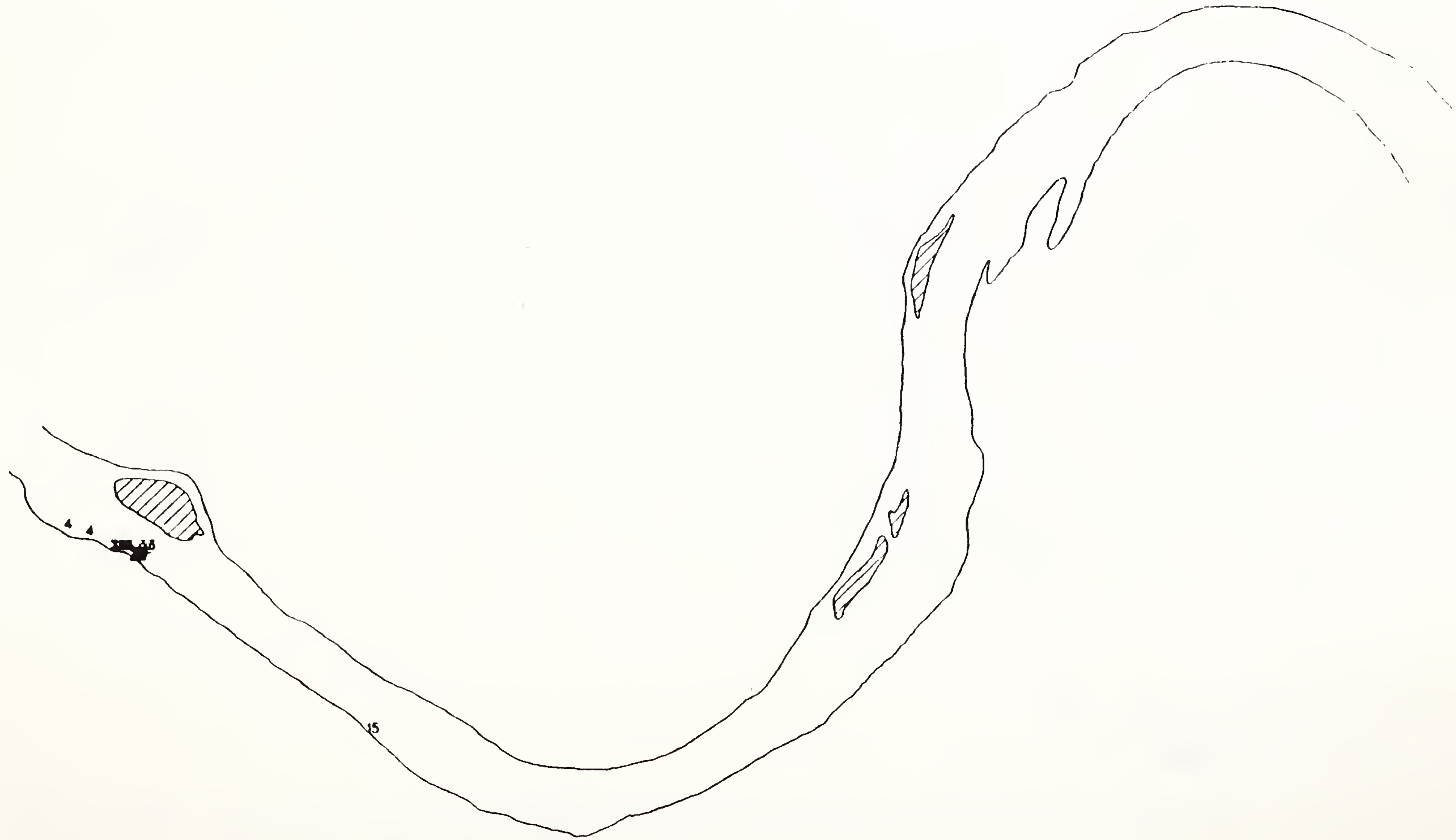


Figure 88. Movement of radio tagged fish 30.215 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

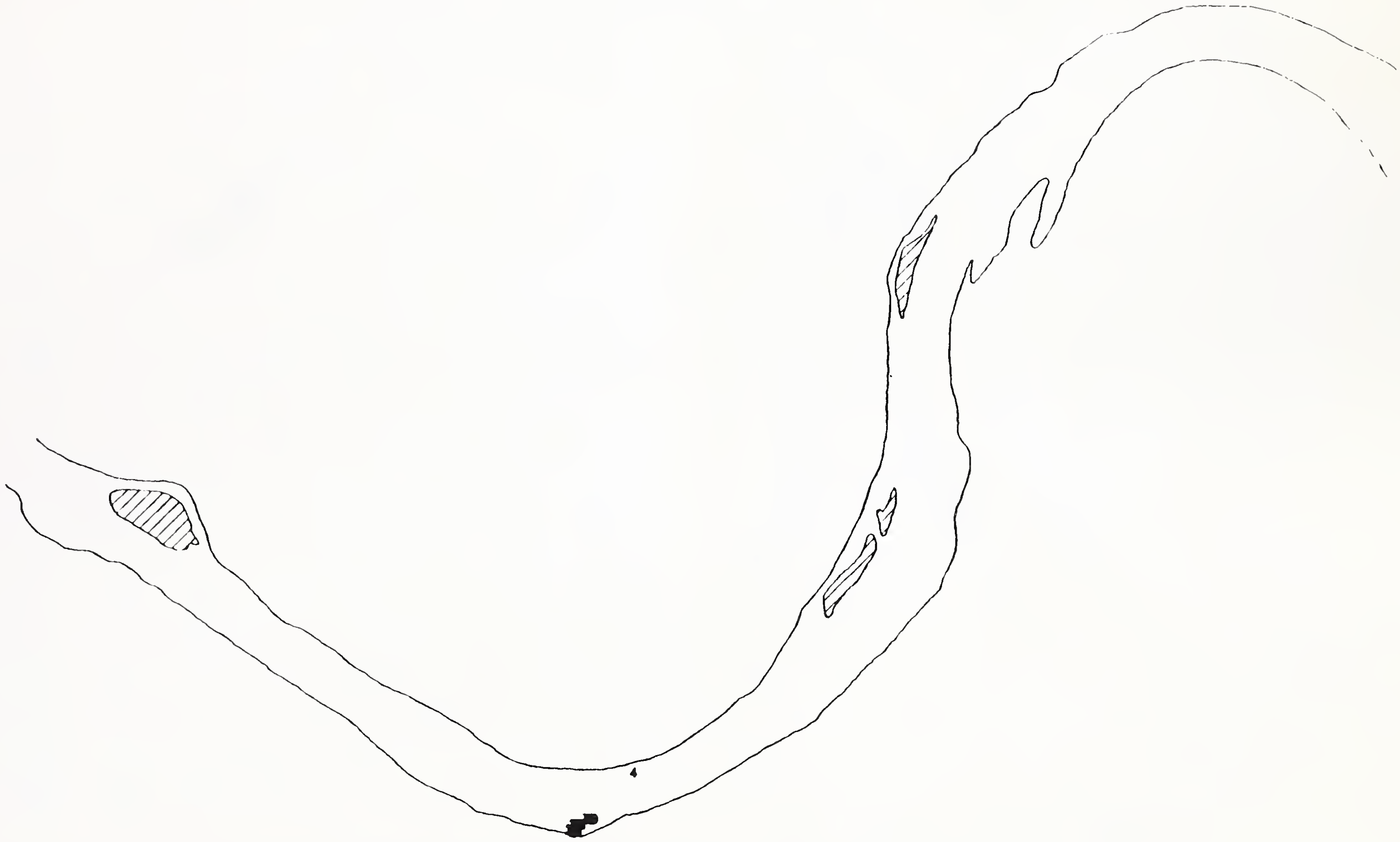


Figure 89. Movement of radio tagged fish 30.227 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

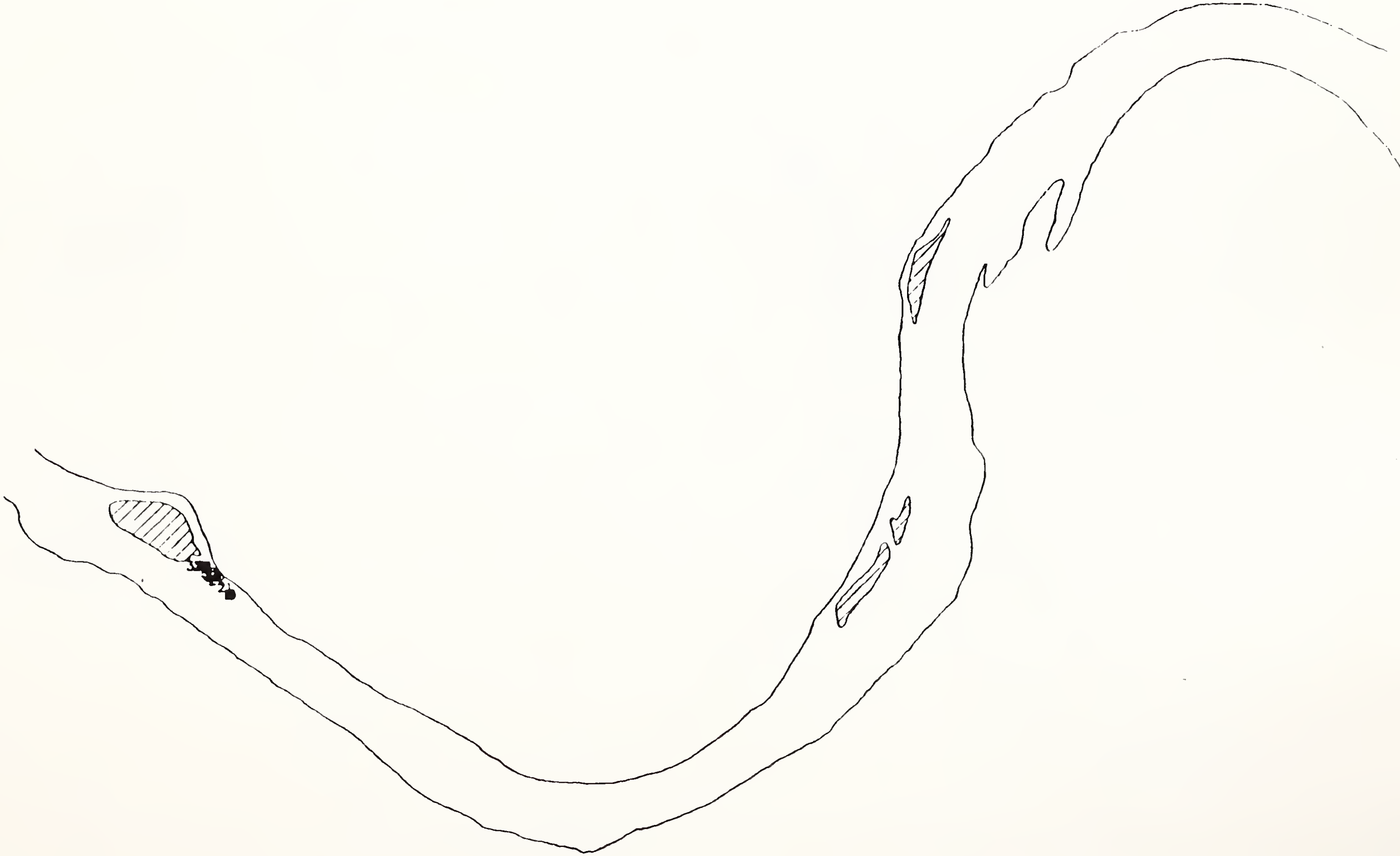


Figure 90. Movement of radio tagged fish 30.237 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

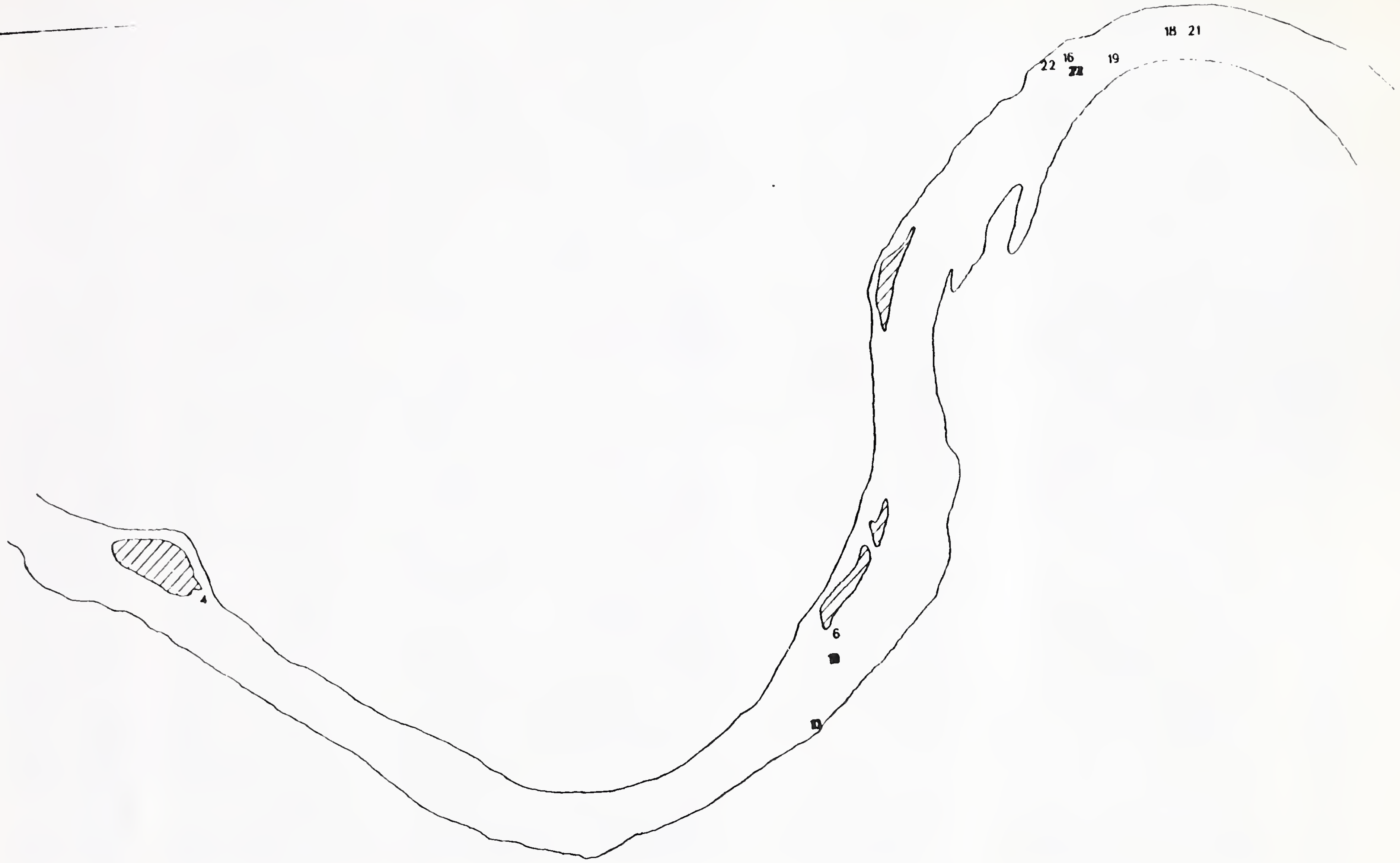


Figure 91. Movement of radio tagged fish 30.276 MHz, Bighorn River, Montana (numbers represent day number, day 4 = release day).

SUMMARY

1. Mean TGP remained more constant through the study area than in previous years and except at Rkm 0.6, mean annual TGP was higher during 1987 than in 1986 or 1985. Maximum delta P's were measured in mid-June and July and the highest individual readings were at Rkm 14.5. Mean annual oxygen, nitrogen and argon, barometric pressure, and temperature values followed the general pattern observed over the last 2 years. Nitrogen and argon were the principal components of hyperbaric pressure downstream to Rkm 2.4 (RM 1.5) through-out the entire year.

2. Oxygen represented an increasingly greater proportion of TGP in the Bighorn River with distance downstream. Oxygen levels as high as 220.1% saturation and 312 mm Hg were measured at Rkm 14.5. Increasing oxygen tension is beneficial to fish since it results in higher threshold levels for cardiovascular system bubble growth and swim bladder overinflation.

3. Bouck gasometers and the continuous monitoring tensionometer at Rkm 0.6 provided similar mean TGP's. Similar comparisons at Rkm 4.8 showed gasometer TGP values to be substantially higher than tensionometer data. Mathematically calculated nitrogen-argon pressures were preferred over tensionometer values. Data transmission over the Hydromet system resulted in elevated readings. Oxygen sensor drift, fouling, or failure on both the Common Sensing tensionometer and Hydrolab 8000 limited the reliability of the data. Fouling of Hydrolab oxygen sensor membranes makes the instrument a poor choice for continuous long term monitoring situations. Tensionometer TGP measurements on the Bighorn River were more precise than at 11 other sites in the Pacific Northwest.

4. Gas tensions in Afterbay Reservoir probably depend on conditions in Bighorn Lake and the river upstream. Rerouting discharge from Afterbay Dam through the sluiceway resulted in higher TGP's in the upper reach of the study area than with spillway release of all water. Mean delta P of cross river transects increased 58, 18, and 24 mm Hg at Rkm 0.6, 4.8, and 14.9, respectively, after discharge was rerouted from the spillway to the sluiceway.

5. In Section 1, GBT incidence was higher on the right bank than on the left bank. The same general pattern of incidence was observed in all 3 years of the study. GBT incidence among trout followed changes in TGP; threshold equations together with TGP appear to explain variations in incidence rates.

6. In the middle section, peak GBT incidence in rainbow trout has always been greater than incidence among brown trout and usually coincides with spawning activity.

7. Survival data did not suggest that TGP and nitrogen tensions increased mortality of embryos from fertilization through eye-up and to the hatching stage. The internal pressure of salmonid eggs and hydrostatic pressure of the water above the redd would provide about 80-120 mm Hg compensating pressure to an embryo in the average rainbow trout redd in the Bighorn River, which would lower uncompensated pressures to under 110% TGP.

8. Mortality of brown trout fry rose rapidly after TGP reached and maintained levels approximately equal to the cardiovascular system threshold. In addition to mortality, buoyancy problems may affect the swimming ability of large numbers of fry, making elevated TGP potentially the most important factor affecting fry survival in the Bighorn River.

9. Minor symptoms of GBT do not appear to remove brown and rainbow trout from the fishable population.

10. Mean daily delta P varied according to flucuations in sluiceway gate openings during much of 1987. Long-term changes in the percentage of total discharge passed through the sluicegates could reduce TGP and may be feasible at times. However, solutions other than operational changes that eliminate or substantially reduce gas supersaturation and allow compliance with water quality standards should be pursued.

11. A predictive model of delta P, superior to those from 1985 or 1986, was developed using stepwise linear regression analysis. Poor predictive ability of actual values at higher gate openings limits the model's usefulness. More appropriate techniques should be applied to the extensive empirical data that have collected.

12. Invertebrate community composition between sites was similar in August 1986, however a significant difference in relative abundance of taxa existed.

13. Four of the five taxa quantified from 1986 benthic samples varied significantly in abundance between sites.

14. Gammarus was more abundant at Rkm 2.4 while Tricorythodes, Serratella, and Simulium were more numerous at Rkm 14.5.

15. Only Tricorythodes and Serratella show possibilities of being affected by gas supersaturation. These as well as other taxa will be evaluated using gas supersaturation bioassays.

16. Two distinct thresholds for bubble growth in salmonids were identified in physiology studies. The primary difference between the two is time to mortality. The first threshold occurs at a water total gas pressure of approximately 1.10 Atmospheres and is independent of water pO2. Bubbles begin to form on gill lamella blocking respiratory water flow; subdermal bubble growth begins on the body surface, especially in the buccal cavity further imparing water flow to the gills. Fish usually survive for more than 100 h.

17. The second threshold for bubble growth is dependent on water pO2 and is about 1.16 Atmospheres at a pO2 of 185 mmHg, sea level conditions and zero depth; mortality occurs in less than 100 h. At this threshold, intra-vascular bubble growth occurs; with increases in pO2, the cardiovascular bubble growth threshold increases and the time of survival increases.

18. Based upon radio tagging data Bighorn River trout do not appear to actively avoid supersaturated gas levels. Trout movements over a large area were not detected, although most radio tagged trout showed localized movements.

19. Seasonal trout movement appeared to be related to changes in availability of energetically suitable habitat. Seasonal changes in the amount and structure of aquatic vegetation appear to influence trout distribution. With the large amount of localized movement of Bighorn River trout, areas that provide hydrostatic compensation depths may provide refuges from exposure to supersaturated water.

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APPENDIX A

Table 1. Means and ranges of water temperature and dissolved gas levels at five sites on the Bighorn River below Afterbay Dam, 1 January - 30 March, 1987.

River km	Sample size	Temp. (C)	D.O. (mg/l)	% saturation		
				Oxygen	N_2+Ar	Total
0.6	36	3.6	12.9	109.1	117.1	115.4
		(2.2-5.8)	(11.7-13.4)	(104.4-113.3)	(110.2-122.3)	(109.9-119.6)
2.4	36	3.8	13.1	111.3	115.0	114.1
		(2.5-5.8)	(11.8-13.7)	(105.3-116.6)	(110.7-120.2)	(109.4-118.7)
4.8	26	4.4	13.9	119.9	110.8	112.6
		(2.8-6.1)	(12.2-14.6)	(109.5-131.8)	(106.8-115.3)	(107.7-117.2)
8.0	36	4.2	14.3	122.4	111.1	113.3
		(2.8-5.8)	(12.1-15.2)	(108.7-135.1)	(107.4-115.2)	(109.5-117.8)
14.5	32	4.7	15.2	132.1	108.5	113.3
		(2.8-7.2)	(12.4-16.5)	(110.7-148.3)	(104.8-115.2)	(107.4-121.8)

Table 2. Means and ranges of barometric, delta P, oxygen, and calculated nitrogen pressures (mm Hg) at five sites on the Bighorn River below Afterbay Dam, 1 January - 30 March, 1987.

River km	B.P. (mm Hg)	^P (mm Hg)	^P-O_2 (mm Hg)	^P-N_2+Ar (mm Hg)	O_2 (mm Hg)	N_2+Ar (mm Hg)
0.6	681	105	13	92	154	626
	(667-690)	(67-134)	(6-19)	(61-119)	(147-161)	(591-654)
2.4	681	96	16	80	157	614
	(666-690)	(64-128)	(7-23)	(57-108)	(148-164)	(587-643)
4.8	680	85	28	57	169	590
	(665-690)	(52-116)	(13-45)	(37-81)	(154-186)	(569-610)
8.0	681	91	32	59	173	593
	(665-690)	(65-120)	(12-49)	(39-82)	(153-190)	(573-619)
14.5	682	90	45	45	187	579
	(666-691)	(50-149)	(15-68)	(26-81)	(156-210)	(563-616)

Table 3. Means and ranges of water temperature and dissolved gas levels at five sites on the Bighorn River below Afterbay Dam, 1 April - 30 June, 1987.

River km	Sample size	Temp. (C)	D.O. (mg/l)	% saturation		
				Oxygen	N_2+Ar	Total
0.6	34	4.9	12.9	112.4	120.0	118.2
		(2.8-6.1)	(12.0-13.5)	(103.2-118.8)	(111.0-124.4)	(109.2-122.7)
2.4	32	5.6	13.7	121.8	118.0	118.6
		(3.9-7.2)	(12.5-14.6)	(110.7-132.0)	(110.8-122.3)	(111.6-122.7)
4.8	33	7.6	15.2	142.6	112.8	118.8
		(3.9-10.3)	(13.2-17.1)	(113.9-166.7)	(108.3-121.3)	(111.5-122.5)
8.0	33	7.4	15.1	140.7	112.5	118.1
		(3.6-9.4)	(13.7-16.8)	(117.5-159.2)	(108.5-117.3)	(112.9-122.5)
14.5	31	9.2	16.0	155.6	107.8	117.5
		(4.4-12.2)	(13.1-18.2)	(123.0-178.4)	(100.3-113.3)	(110.6-122.5)

Table 4. Means and ranges of barometric, delta P, oxygen, and calculated nitrogen pressures (mm Hg) at five sites on the Bighorn River below Afterbay Dam, 1 April - 30 June, 1987.

River km	B.P. (mm Hg)	^P (mm Hg)	^P-O_2 (mm Hg)	^P-N_2+Ar (mm Hg)	O_2 (mm Hg)	N_2+Ar (mm Hg)
0.6	680	124	18	106	159	639
	(667-690)	(63-153)	(5-26)	(58-129)	(146-167)	(593-661)
2.4	680	126	31	95	172	628
	(667-690)	(79-153)	(15-46)	(57-117)	(155-188)	(588-652)
4.8	681	128	60	68	201	599
	(667-690)	(78-153)	(20-95)	(44-113)	(161-237)	(573-647)
8.0	681	123	57	66	198	598
	(667-691)	(88-153)	(25-83)	(45-91)	(168-224)	(575-620)
14.5	681	119	78	41	219	572
	(668-691)	(71-153)	(32-111)	(1-71)	(171-254)	(528-605)

Table 5. Means and ranges of water temperature and dissolved gas levels at five sites on the Bighorn River below Afterbay Dam, 1 July - 30 September, 1987.

River km	Sample size	Temp. (C)	D.O. (mg/l)	% saturation Oxygen	% saturation N_2+Ar	% saturation Total
0.6	33	11.3	10.4	105.6	118.4	115.4
		(6.7-15.6)	(8.5-12.8)	(96.9-117.1)	(113.1-124.9)	(110.1-121.9)
2.4	33	11.7	11.6	119.4	116.1	116.6
		(7.2-15.8)	(9.4-14.0)	(101.6-135.5)	(111.5-121.9)	(111.0-122.6)
4.8	33	13.7	14.3	154.1	108.1	117.3
		(8.3-17.2)	(10.4-18.7)	(107.3-197.1)	(100.4-114.8)	(109.3-127.9)
8.0	32	13.5	13.9	148.8	108.8	116.9
		(7.8-16.9)	(9.7-18.0)	(104.7-187.1)	(102.7-114.2)	(108.2-126.0)
14.5	33	14.7	14.6	161.3	105.1	116.4
		(8.9-18.1)	(9.6-20.2)	(103.5-220.1)	(98.8-114.4)	(106.2-128.0)

Table 6. Means and ranges of barometric, delta P, oxygen, and calculated nitrogen pressures (mm Hg) at five sites on the Bighorn River below Afterbay Dam, 1 July - 30 September, 1987.

River km	B.P. (mm Hg)	^P (mm Hg)	^P-O_2 (mm Hg)	^P-N_2+Ar (mm Hg)	O_2 (mm Hg)	N_2+Ar (mm Hg)
0.6	680	105	8	97	148	626
	(671-691)	(68-148)	(-4-24)	(69-132)	(134-165)	(593-664)
2.4	680	112	27	85	167	614
	(671-691)	(76-154)	(2-50)	(61-116)	(143-191)	(587-648)
4.8	680	118	76	42	216	570
	(671-691)	(63-188)	(10-137)	(2-78)	(151-277)	(522-608)
8.0	679	115	68	46	208	575
	(672-689)	(56-177)	(7-123)	(14-75)	(146-264)	(540-605)
14.5	680	112	86	26	226	554
	(673-691)	(42-191)	(5-168)	(-7-60)	(145-312)	(523-590)

Table 7. Means and ranges of water temperature and dissolved gas levels at five sites on the Bighorn River below Afterbay Dam, 1 October - 31 December, 1987.

River km	Sample size	Temp. (C)	D.O. (mg/l)	% saturation Oxygen	% saturation N_2+Ar	% saturation Total
0.6	32	11.0	10.5	105.9	119.2	116.2
		(6.1-15.6)	(8.7-12.3)	(97.1-113.7)	(112.1-124.1)	(109.5-120.9)
2.4	26	11.8	10.9	112.8	115.6	114.7
		(7.5-15.8)	(9.8-12.1)	(101.6-122.5)	(108.8-119.7)	(108.5-118.9)
4.8	27	12.0	12.2	127.2	109.7	113.1
		(7.2-16.7)	(9.8-13.7)	(102.7-157.0)	(102.9-119.4)	(106.8-116.2)
8.0	32	11.2	12.3	125.1	108.9	112.1
		(6.1-16.7)	(10.2-13.5)	(102.3-151.3)	(103.1-112.3)	(106.3-114.8)
14.5	26	11.8	12.8	133.3	104.9	110.6
		(6.7-17.2)	(10.2-14.4)	(100.7-166.2)	(98.6-110.7)	(102.9-115.6)

Table 8. Means and ranges of barometric, delta P, oxygen, and calculated nitrogen pressures (mm Hg) at five sites on the Bighorn River below Afterbay Dam, 1 October - 31 December, 1987.

River km	B.P. (mm Hg)	^P (mm Hg)	^P-O_2 (mm Hg)	^P-N_2+Ar (mm Hg)	O_2 (mm Hg)	N_2+Ar (mm Hg)
0.6	678	110	8	101	148	629
	(670-687)	(65-141)	(-4-19)	(64-127)	(135-159)	(590-655)
2.4	677	100	18	82	158	609
	(670-687)	(58-128)	(2-32)	(46-103)	(143-172)	(576-632)
4.8	678	89	38	51	178	578
	(670-687)	(46-110)	(4-80)	(15-103)	(145-221)	(544-634)
8.0	678	82	35	47	175	574
	(669-688)	(43-100)	(3-72)	(16-64)	(144-212)	(546-592)
14.5	678	72	47	25	186	553
	(669-689)	(20-105)	(1-92)	(-8-57)	(142-230)	(521-588)

Table 9. Differences between manual measurements and readings from the Common Sensing Tensionmeter during calibration at the Saint Xavier gagehouse (Rkm 0.6), Bighorn River, 5 January - 30 December, 1987. (An H after the date indicates that tensionmeter readings were obtained via the Hydromet system.)

	Deviation from manual:			
Date	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)	Barometric pressure (mm)
1/5 - H	0.0	-6	+8	+3
1/7	0.0	-7 *	+7 *	+1 *
1/9 - H	-0.1	+4	-3	+1
1/12		**		
1/12	-0.2	-3	-3	0
1/14 - H	0.0	+5	+4	+2
1/16 - H	+0.1	+1	+2	+2
1/19 - H	-0.1	+5	-3	+2
1/23 - H	0.0	+5	+3	+2
1/26 - H	+0.1	+2	+3	+2
1/28 - H	+0.2	+7	+4	+3
1/30 - H	+0.3	+1	+5	+2
2/2 - H	0.0	+7	-1 *	+3
2/4 - H	-0.2	0	+3	+3
2/6 - H	0.0	+7	-2	+2
2/9 - H	-0.2	+1	-3	+2
2/12 - H	-0.3	+5	-3	+1
2/16	-0.1	+8	-3	+1
2/18	-0.1	-5	-2	0
2/23	-0.2	-3	+1	-
2/25	0.0	-6	+3	-1
2/27	-0.1	+1	0	0
3/2	-0.3	-4	-5	0
3/4	-0.3	-7	-8	-1
3/6	-0.3	-7	-4	0
3/9	-0.4	0	-3	-1
3/11	-0.4	+5	+2	+1
3/13	-0.3	+1	-4	0
3/16	-0.2	0	0	0
3/18	-0.2	-5	-6	0
3/20	-0.1	+6	-1	+1
3/23	-0.2	+2	0	0
3/25	-0.3	-6	-6	0
3/27	-0.2	-1	-4	0

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 9. (continued).

Date	Deviation from manual:			
	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)	Barometric pressure (mm)
3/30	-0.2	-3	-5	0
4/1	+0.2	+3	-4	+1
4/2		**		
4/3	0.0	-	-3	0
4/4	0.0	+5	+1	+1
4/6 - H	0.0	+7	-9	+1
4/8	+0.1	0	-2	0
4/10	-0.5	-5	-9	0
4/12	-0.2	+1	-1	0
4/18	-0.2	-1	-2	+1
4/21	-0.3	+5	-12	0
4/26	-0.1	+6	0	0
5/1	+0.1	-13	-2	+1
5/4	-0.2	-12 *	-13	0
5/8	-0.1	+3	-2	0
5/11	0.0	-1	-2	+1
5/13	-0.3	-4	-6	-1
5/15	-0.1	+1	-6	-1
5/18	-0.1	-12	-8	0
5/22	-0.3	-4	-13 *	0
5/27	-0.1	0	-4	0
5/29	-0.1	-1	+5	0
6/1 - H	-0.2	+3	0	+2
6/3 - H	+0.1	-2	-4	+3
6/5 - H	-0.3	+5	+8	+3
6/8	-0.3	+2	+5	0
6/10	0.0	+1	+3	0
6/12	-0.1	-3	+8	0
6/15	0.0	-2	+12 *	+1
6/17	-0.2	-5	-5	0
6/19	-0.1	+9	-1	0
6/22	0.0	+15	-2	+1
6/24	-0.1	+6	-11	0
6/26	+0.1	+8	-10	0
6/26		**		
6/29	+0.2	+8	-6	0
7/1	-0.3	+6	-5	0
7/3	+0.1	+5	-7	+1
7/6	-0.1	+7	-5	+1

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 9. (continued).

	Deviation from manual:			
Date	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)	Barometric pressure (mm)
7/8	-0.1	+9	0	0
7/10	0.0	+11	-3	0
7/13	-0.2	+5	-11	-1
7/15	-0.2	-2	-7	+1
7/17	-0.1	+5	+7	0
7/20	-0.1	0	-9	0
7/22	-0.2	-1	-7	-1
7/24	0.0	+4	-5	0
7/27	+0.2	+3	+5	+1
7/29	+0.1	+6	+4	0
7/31	+0.3	+9	+13	+1
8/3	-0.1	+19	-9	0
8/5	+0.1	+9	-3	+1
8/7	+0.1	+7	+6	+1
8/10	0.0	+7	+4	0
8/11		*		
8/12	-1.1	+5	0	0
8/14	-0.9	+1	0	-
8/19	+0.1	+1	-20	-
8/21	-8.8	+1	-4	-
8/24	-11.8	+8	-9	-
8/26	+0.1	+3	-13	-
8/26	+0.3	-	-14	-
8/27			*	
8/28	+0.4	+1	-1	-
8/31	+0.1	+8	+5	-
9/2	+0.1	+16	+9	0
9/4	0.0	+4	+6	0
9/8	+0.3	+5	+4	0
9/11	+0.1	+6	+4	+1
9/13	+0.3	+2	0	+1
9/19	+0.1	0	-6	0
9/26	+0.1	+1	+5	0
10/2	+0.1	-13	-1	0
10/5	0.0	-17	-8	0
10/7	-0.1	+7	-7	+1
10/9	+0.2	-18	-11	0
10/10		**		
10/13	0.0	-1	-13	-1

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 9. (continued).

Date	Deviation from manual: Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)	Barometric pressure (mm)
10/16	+0.1	+2	-21	0
10/19	0.0	+4	-13	0
10/21	+0.1	+7	0	0
10/23	0.0	+10	-9	0
10/26	-0.1	+1	-4	0
10/29	-0.2	+3	+2	0
11/2	0.0	+9	-8	0
11/4	0.0	+5	-8	0
11/6	0.0	+9	-13	0
11/9	-0.2	+6	-18	0
11/10		**		
11/13	+0.1	+4	0	0
11/16	-0.2	+1	-2	+1
11/20	-0.3	+8	-18	0
11/23	+0.1	+8	-18	0
11/25	0.0	+6	-1	0
11/30	+0.1	+8	-12	0
12/2	-0.2	0*	-9*	0
12/4	-0.1	-2	-8	0
12/7	0.0	+5	-15	0
12/9	+0.2	-2	-7	0
12/11	+0.1	-1	-18	0
12/16	-0.1	+6	-12	0
12/18	-0.5	0	-23	0
12/21	0.0	+4	-3*	+1
12/23	+0.1	+2	+3	0
12/28	-0.4	+1	-3	0
12/30	+0.1	+19	-3	0

* - asterisk indicates that a calibration adjustment was made.
** - a double asterisk indicates that the silastic tubing was changed.

Table 10. Differences between manual measurements and readings from the Hydrolab System 8000 at the Saint Xavier gagehouse (Rkm 0.6), Bighorn River, 5 January - 30 December, 1987. (An H after the date indicates that tensionmeter readings were obtained via the Hydromet system.)

	Deviation from manual:	
Date	Temperature (C)	Oxygen pressure (mm)
1/5 - H	+3.4	-96,-96
1/7	-0.5	-95,-75
1/9 - H	+3.3	-91,-91
1/13	-0.8	-18,-18
1/14 - H	+3.6	-13,-11
1/16 - H	+3.5	-16,-15
1/19 - H	+3.6	-19,-21
1/23	+3.6	-13,-22
1/26 - H	+3.7	-14,-16
1/28	+3.7	-14,-21
1/30 - H	+3.9	-25,-15
2/2 - H	+3.4	-13,-13
2/4 - H	+3.5	-18,-18
2/6 - H	+3.5	-9,-13
2/9 - H	+3.4	-13,+2
2/12 - H	-	-59,-74
2/16	-0.7	-17,-18
2/18	-0.7	-16,-17
2/23	-0.8	-9,-16
2/25	-0.6	-3,-14
2/27	-0.8	-6,-14
3/2	-1.0	+1,-15
3/4	-1.0	-1,-16
3/6	-0.9	0,-13
3/9	-1.1	+1,-12
3/11	-0.8	+31,+22
3/13	-0.9	-1,-10
3/16	-0.9	0,-13
3/18	-0.9	-1,-14
3/20	-0.8	-2,-14
3/23	-0.9	-15,-16
3/25	-1.1	-16,-20
3/27	-0.9	-16,-17
3/30	-0.8	-20,-20
4/1	-0.4	-18,-19
4/3	-0.7	-19,-19
4/4	-0.5	-18,-18
4/8	-0.5	-11,-14
4/10	-1.2	+13,-11

Table 10. (continued).

	Deviation from manual:	
Date	Temperature (C)	Oxygen pressure (mm)
4/12	-0.9	-9,0
4/18	-0.9	-2,-11
4/21	-1.0	+4,-7
4/26	-0.8	-10,-15
5/1	-0.6	-14,-15
5/4	-0.9	-3,-9
5/8	-0.7	-5,-11
5/11	-0.7	-6,-9
5/13	-1.0	-10,-19
5/15	-0.8	-21,-21
5/18	-0.6	-11,-12
5/22	-0.9	-9,-15
5/27	-0.8	-10,-16
5/29	-0.8	-14,-14
6/8	-1.2	-1,-13
6/10	-0.8	+6,-12
6/12	-0.9	-2,-28
6/15	-0.7	+7,-22
6/17	-1.0	-11,-23
6/19	-0.8	-79,-81
6/22	-0.7	-98,-105
6/24	-0.9	-109,-116
6/26	-0.7	-114,-118
6/29	-0.6	-55
6/30 - calibrated		
7/1	-1.0	-10,-17
7/3	-0.7	-15,-18
7/6	-1.0	-29
7/8	-1.0	-2,-14
7/10	-1.0	+15
7/13	-1.0	+25
7/15	-1.0	-7,-10
7/17	-0.9	-2,-7
7/20	-0.9	-5,-6
7/22	-1.1	+34,-5
7/24	-0.9	+4,-5
7/27	-0.7	-2,-3
7/29	-0.8	-3,+6
7/31	-0.6	-10,-14
8/3	-1.0	+44,+16
8/5	-0.8	-4,-8
8/7	-0.7	-20,-18

Table 10. (continued).

Date	Deviation from manual:	
	Temperature (C)	Oxygen pressure (mm)
8/10	-0.9	+8,+4
8/12	-0.9	+4,+4
8/14	-0.7	+6,+1
8/19	-0.8	+33,+26
8/21	-0.7	+149,+36
8/24	-0.9	+56,+16
8/26	-0.7	+8,+13
8/28	-1.3	+48,+5
8/31	-0.8	+100,+27
9/2	-0.8	+52,+14
9/4	-0.8	+25,+4
9/8	-0.5	+26,+18
9/11	-0.7	+16,+13
9/13	-0.6	+142,+28
9/19	-0.6	-11,-14
9/26	-0.6	-19,-17
10/2	-0.8	-14,-13
10/5	-0.8	-14,-17
10/7	-0.9	-21,-28
10/9	-0.6	-32,-32
10/13	-0.8	-21,-21
10/16	-0.7	-20,-20
10/19	-0.8	-52,-21
10/21	-0.6	-49,-30
10/23	-0.8	-66,-57
10/26	-0.8	-72,-59
10/29	-0.9	-107,-70
11/2	-	-
11/4	-	-
11/6	-	-
11/9	-	-
11/13	-	-
11/15	-	-
11/16	-0.9	-13,-14
11/20	-1.0	-16,-16
11/23	-0.6	-16,-18
11/25	-0.7	-14,-15
11/30	-0.5	-20,-20
12/2	-0.9	+3,+2
12/4	-0.8	-18,-18
12/7	-0.7	-19,-18
12/9	-0.5	-14.-14

Table 10. (continued).

Date	Deviation from manual:	
	Temperature (C)	Oxygen pressure (mm)
12/11	-0.7	-18,-17
12/16	-1.0	-19,-21
12/18	-1.0	-14,-15
12/21	-0.7	-14,-14
12/23	-0.6	-20,-19
12/28	-1.2	-16,-18
12/30	-0.6	-23,-23

Table 11. Differences between manual measurements and readings from the Common Sensing Tensionmeter during calibration at Rkm 4.8, Bighorn River, 5 January - 21 December, 1987.

	Deviation from manual:		
Date	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)
12/28/86 - DCP quit collecting and transmitting data			
1/5/87 - Battery voltage too low to transmit			
1/12 - New Common Sensing Tensionometer installed			
1/19 - DCP began transmitting at 15:00			
1/21	0.0	+3	+53
1/22			*
1/23	-0.2	-13	-4
1/26	-0.4	-18	-6
1/28	-0.3	-14	-6
1/29	*	*	*
1/30	0.0	+1	-1
2/2	+0.1	-10	0
2/3		*	
2/4	0.0	+17	-3
2/6	-0.2	+22 *	-3 *
2/9	+0.1	-25	+1
2/10		*	
2/12	+0.1	+4	-4
2/16	+0.4	+10 *	-2
2/18	-0.1	-20	+4
2/20	+0.1	-21	+8
3/2	+0.1	-20	+3
3/4	-0.6	-29	-3
3/6	+0.2	-29	-1
3/11	+0.3	-6	-3
3/13	-0.1	-33	-5
3/16	+0.4	+9	+1
3/18	0.0	-25	+1
3/20	+0.4	-13	+23
3/23	-0.1	-17	-17
3/25	0.0	-30	-18
4/1	+0.1	+27	-3
4/2		**	
4/4	+0.4 *	+49 *	+6 *
4/6	-0.4	-7	-17
4/8	-0.4	-10	-17
4/10	-0.5	-5	-9

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 11. (continued).

Date	Deviation from manual: Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)
4/12	-0.3	+6 *	-18 *
4/18	-0.5	-9 *	-26 *
4/21	-0.4	-5	+22
4/24	-0.4	-2	+2
4/26	-0.3	+6	+29 *
5/1	+0.2	-8	-34 *
5/4	-0.6	-7 *	-15
5/8	-0.7	-5	-21
5/10			*
5/11	-0.7 *	+4	+10 *
5/13	+0.5	-4	-4
5/15	+0.1	0	-4
5/18	+0.6	+11	+4
5/22	+0.4	-5	+24
5/27	+0.5	-2	-9
5/29	+0.1	-20	-16
6/1	+0.5	-19	-3
6/3	+0.2	-23	-6
6/5	+0.3	-19	-3
6/8	+0.2	+2	-1
6/10	-1.8	+21	-22
6/12	-2.2	-8	-4
6/15	-1.5 *	-1	-1
6/17	-0.5	+1	-1
6/19	+1.0	+10	+14
6/22	+1.3	+15	+24
6/24	-0.4	+5	+29
6/26	0.0	-2	+31
6/26		**	
6/29	+0.5	-23	+37
6/30			*
7/1	+0.2	-27	+2
7/3	+1.0*	+10*	-11*
7/6	-0.9	-93	-50
7/8	-0.7	-58*	-188
7/10	+0.2	+26	+28
7/13	-1.3	+15	+28
7/15	-1.7	-30	+28
7/16	*		*

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 11. (continued).

	Deviation from manual:		
Date	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)
7/17	+2.1	+79	+35
7/20	+0.3	-46	-57
7/22	+0.2	-27	-85
7/24	+0.3	-22	-87
7/27	+1.2	+13	-78
7/28	-0.1	-59* **	-46 or +21*
7/29	+0.1		+71
7/30		**	
7/31	+1.8		+76
8/3	Replaced control unit and probe.		
8/3	-1.5*	+2	+55
8/5	+0.2	+8	-37
8/7	+1.7	+8	+44
8/10	+0.2	+1	+4
8/12	+0.4	-3	-31
8/14	+1.5	+3	-19
8/19	+0.5	+19	-12*
8/21	+0.6	-1	-11
8/24	+1.4	+15	-20
8/26	+1.4	+12	+3
8/27	*	*	
8/28	+0.4	-16	-10
8/31	-0.9	-15	-20
9/1		*	
9/2	-0.7	-13	-16
9/4	+0.9	-14	+46
9/8	+0.3	+4	-22
9/11	+0.4	+5	+18
9/13	-0.3	+16	-12
9/19	-0.2	+9*	-81*
9/26	+0.6	-6*	-29*
10/2	+0.3	-1	+743*
10/5	+0.2	-2	-19
10/7	+0.6	+3	-3
10/9	+1.2	-1	-14
10/13	+0.8	-5	-14
10/16	+0.3	+9	+3
10/19	+0.8	+8	+33
10/21	+0.5	+20	+51

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 11. (continued).

Date	Deviation from manual:		
	Temperature (C)	Total gas pressure (mm)	Oxygen pressure (mm)
10/23	+0.3	+14	+42
10/26	+0.4	+14	+41
10/29	-0.1	+8	+37
11/2	+0.6	+19	+63
11/4	+0.5	+4	+38
11/6	+0.4	+9	+43
11/9	+0.3	+5	+38
11/13	+0.8	+1**	+46
11/16	+0.7	+4	+52
11/20	+0.7	+13	+39
11/23	+0.7	+18	+48
11/25	+1.0	+15	+79
11/30	+0.6	+16	+58
12/2	+0.5*	+2*	+14*
12/4	0.0	-5	+6
12/7	+0.1	+4	+6
12/9	+0.3	+12	+13
12/11	+0.5	+18	+9
12/18		*	
12/21	+0.5	+3	+7

* - asterisk indicates that a calibration adjustment was made.

** - a double asterisk indicates that the silastic tubing was changed.

Table 12. Differences between manual measurements and readings from the Hydrolab System 8000 at Rkm 4.8, Bighorn River, 5 January - 21 December, 1987.

Date	Deviation from manual: Temperature (C)	Oxygen pressure (mm)
1/5	-0.7	+11,+9
1/19 - DCP began transmitting at 15:00		
1/21	-0.1	+43,+28
1/23	-0.4	+40,+30
1/26	-0.6	+31,+34
1/28	-0.3	+40,+27
1/30	-0.5	+33,+29
2/2	-0.3	+32,+25
2/4	-0.4	+34,+27
2/6	-0.6	+28,+18
2/9	-0.3	+33,+25
2/12	-0.4	+44,+27
2/16	-0.1	+30,+29
2/18	-0.8	+48,+30
2/20	-0.5	+40,+36
3/2	-0.7	+43,+37
3/4	-1.3	+58,+42
3/6	-1.1	+56,+40
3/11	-0.8	+31,+6
3/13	-1.0	+55,+40
3/16	-0.7	+35,-1
3/18	-0.9	+67,+39
3/20	-0.5	+28,+30
3/23	-0.7	-9,-25
3/25	-0.5	-11,-18
4/1	-0.5	-12,-11
4/4	-0.2	+3,+1
4/6	-0.5	+2,-1
4/8	-0.5	+10,+6
4/10	-1.2	+13,-11
4/12	-0.5	-5,+6
4/18	-0.7	-4,-3
4/21	-0.7	+3,-7
4/24	-0.6	-7,-6
4/26	-0.5	-7,-5
5/1	-0.1	-10,-11
5/4	-0.9	-12,-13
5/8	-0.9	-13,-18
5/11	-1.1	-22,-18
5/13	-0.4	-34,-31
5/15	-0.7	-19,-19

Table 12. (continued).

Date	Deviation from manual: Temperature (C)	Deviation from manual: Oxygen pressure (mm)
5/18	-0.3	-17,-26
5/22	-0.5	-90,-20
5/27	-0.4	-11,-14
5/29	-0.5	-26,-30
6/1	-0.1	-18,-22
6/3	-0.6	-26,-36
6/5	-0.6	-10,-19
6/8	-0.7	-15,-21
6/10	-2.6	-25,-18
6/12	-3.1	-53,-64
6/15	-0.7	+7,-22
6/17	-2.9	-50,-57
6/19	-1.4	-8,-5
6/22	-1.1	-25,-24
6/24	-1.9	-38,-50
6/26	-2.4	-19,-28
6/29	-1.9	-21,-30
7/1	-2.6	-28,-27
7/3	-1.4	-20,-30
7/6	-1.9	-38,-40
7/10	-1.1	-28,-34
7/13	-2.6	-67,-76
7/15	-3.0	-83,-92
7/17	-0.9	-22,-27
7/20	-2.7	-86,-110
7/22	-2.8	-85,-96
7/24	-2.7	-87,-121
7/27	-1.8	-47,-38
7/28	-3.1	-43,-54
7/29	-2.9	-63,-59
7/31	-1.2	+7,-2
8/3	-2.4	-20,-35
8/5	-2.3	-38,-51
8/7	-0.7	-11,-13
8/10	-2.3	-43,-52
8/12	-1.9	-54,-58
8/14	-0.9	-15,-13
8/19	-2.0	-13,-15
8/21	-1.8	-46,-51
8/24	-1.1	-23,-28
8/26	-1.3	-21,-26
8/28	-1.5	-35,-33
8/31	-2.0	-43,-47

Table 12. (continued).

Date	Deviation from manual: Temperature (C)	Oxygen pressure (mm)
9/2	-1.8	-25,-53
9/4	-0.4	-5,-5
9/8	-1.5	-41,-58
9/11	-0.6	-30,-23
9/13	-1.4	-29,-68
9/19	-1.3	-60,-67
9/26	-0.5	-43,-43
10/2	-0.8	-36,-37
10/5	-0.8	-20,-22
10/7	-0.4	0,-18
10/9	+0.2	-16,-75
10/13	+10.7	-53,-66
10/16	+3.0	-88,-84
10/19	+13.7	-49,-61
10/21	+16.8	-32,-24
10/23	+13.6	-29,-20
10/26	+27.2	0,-22
10/29	+19.6	-19,-43
11/2	+9.1	-33,-47
11/4	+30.1	-53,-69
11/6	+15.7	-60,-73
11/9	+6.7	-29,-76
11/13	+6.3	-51,-58
11/16	+6.1	-61,-61
11/20	+5.9	-75,-85
11/23	+6.2	-25,-81
11/25	+5.9	-26,-39
11/30	+5.5	-76,-83
12/2	+6.2	-68,-70
12/4	+5.7	-87,-88
12/7	+5.9	-83,-81
12/9	+6.3	-45,-63
12/11	+23.5	-47,-61
12/21	+18.0	-23,-25

APPENDIX B

Table 1. Checklist of aquatic insects found at Rkm 2.5 and 14.5 below Yellowtail Afterbay Dam, on the Bighorn River, Montana

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Ephemeroptera
- *Baetis tricaudatis*
- *Seratella micheneri*
- *Tricorythodes sp.*
- *Choroterpes sp.*

Trichoptera
- *Amiocentrus sp.*
- *Brachycentrus sp.* (adult only)
- *Hydropsyche sp.*
- *Hydroptila sp.*

Plecoptera
- *Isoperla sp.*
- *Amphinimura sp.* (a single individual-Rkm 2.4)

Coleoptera
- *Optioservus sp.*

Diptera
- Simulidae
  - *Simulium sp.*
- Chironomidae
- Tipulidae
- Ceratopogonidae
- Sciomyzidae

Amphipoda
- *Gammarus lacustrus*
- *Hyallela azteca*

Gastropoda
- *physella sp.*

Oligochaetae

Planaria

EFFECTS OF GAS SUPERSATURATED WATER ON JUVENILE BROWN AND RAINBOW TROUT

by

William Paul Connor

A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

Fish and Wildlife Management

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Bozeman, Montana

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ABSTRACT

Six bioassays were conducted at the Bozeman Fish Technology Center using juvenile brown trout (_Salmo_ _trutta_) and rainbow trout (_Salmo_ _gairdneri_). Juveniles of both species were exposed for 30-d to 104%, 112%, and 125% gas supersaturated water. No significant mortality occurred in the 112% treatment except during two tests when percent total gas pressure exceeded 113%, indicating that a critical threshold exists above this pressure. As fish grew they became more susceptible to 125% gas supersaturation. Total mortality and mortality rate were less when fish were small. The frequency at which emphysema occurred by body region also varied with fish size and smaller fish died with different external symptoms than larger fish. Larger fish were more likely to die faster than smaller fish and with no external symptoms. Daily mortality of brown trout exposed to 125% gas supersaturation was always significantly greater than for rainbow trout of similar size. Juvenile brown trout that survived exposure to 112% supersaturation showed greater incidence of external symptoms of GBT than juvenile rainbow trout of similar size. Juvenile rainbow and brown trout recovery after exposure to 117% gas supersaturated water varied according to external symptom severity. Fish that did not recover usually had severe exopthalmia. Juvenile brown trout, repeatedly exposed to 118% gas supersaturated water, given 30-d to recover between exposures, developed more severe symptoms with each exposure. Surviving fish developed new symptoms more often than recurring symptoms. Growth of the medium treatment (111%) survivors was not different from control fish. There was no difference in vulnerability to predation in circular tanks between juvenile brown and rainbow trout caused by exposure to gas supersaturation. Predation tests conducted in an artificial stream suggested some difference in susceptibility may be present, but data were not conclusive. Bacterial challenges indicated that juvenile brown trout exposed to 118% gas supersaturated water for 5-d were more susceptible to infection by _Aeromonas_ _hydrophila_ than non-exposed fish.

INTRODUCTION

Supersaturation of water with atmospheric gases is directly responsible for occurrence of Gas Bubble Trauma (GBT) in fishes. Bouck (1980) and Fidler (1985) described GBT as a noninfectious process in fishes and invertebrates promoted by pressure disequilibrium between liquid and gas phases, that produces primary lesions in blood (emboli) and in tissues (emphysema) and subsequent dysfunctions. Recent literature reviews thoroughly examine history and causes of GBT (Bouck 1980, Weitkamp and Katz 1980). Gas bubble trauma is commonly a problem in river-reaches below dams. This is the case on the Bighorn River downstream from Yellowtail Afterbay Dam.

The Yellowtail Afterbay Dam reregulates peaking discharges from Yellowtail Dam and provides uniform daily discharge into the Bighorn River. Supersaturation of dissolved gases results from entrainment of air as water passes through the gates of the Afterbay Dam, particularly the sluiceway gates.

Several supersaturation studies on the Bighorn River (Swedburg 1973, Porter and Viel 1980, Curry and Curry 1981, and White et al. 1987) have expanded our knowledge of effects of supersaturation of dissolved gases on large river fisheries. However, there are still many factors that complicate our understanding of GBT in fishes. These factors include possible differential susceptibility according to fish species and size, the ability of salmonids to recover from GBT, and the indirect effects of exposure to GBT on juvenile brown and rainbow trout.

Variations in fish response to gas supersaturated water have been noted for different sizes and species of fish. Jensen et al. (1986) predicted that larger fish would be more sensitive to gas supersaturated water than smaller fish. White et al. (1987) found that large brown trout in the Bighorn River have more severe symptoms of GBT than smaller brown trout. In general it is believed that susceptibility differs among life stages and sizes within a species (Weitkamp and Katz 1980).

Some salmonid species may be less tolerant of gas supersaturated water than others. Fredenberg (1985) and White et al. (1987) observed that Bighorn River brown trout (_Salmo trutta_) were more susceptible to GBT than rainbow trout (_Salmo gairdneri_) of similar size.

An early study on effects of gas supersaturated water on marine fishes showed external signs of GBT regressed within 24-h after removal to unsaturated water (Gorham 1901). Information pertaining to brown and rainbow trout recovery from GBT is scarce. Subsequent to extended periods of low percent total gas pressure (TGP), emphysema was superseded by dark patches of scar tissue on brown trout of the Bighorn River (George Liknes pers. comm.). However, the time needed for this recovery is uncertain.

Repeated exposure may influence the time of recovery after initial exposure to gas supersaturated water. Weitkamp and Katz (1980) implied that intermittent exposure may increase the level of supersaturation fish can tolerate by increasing the time over which a specific exposure accumulates. Alternatively, scar tissue formed during recovery from prior exposure could accelerate formation of GBT symptoms by providing nucleation sites with larger surface area. Also, stress associated with the physiological insult brought on by gas supersaturated water and the subsequent recovery response could lead to indirect mortality.

Indirect mortality resulting from sublethal effects of GBT have not been thoroughly investigated and may be a factor influencing fish species composition of rivers with gas supersaturation problems. This phenomenon may occur on the Bighorn River where brown trout number over 7,700 fish/km in the 1.6 km below afterbay dam, while rainbow trout number approximately 350 fish/km (White et al. 1987). Indirect mortality could be manifested as increased susceptibility to predation or disease.

Swimming ability can also be affected by exposure to gas supersaturated water. Juvenile chinook salmon (Oncorhynchus tschawytscha) exposed to 106% - 120% gas supersaturated water swam significantly poorer than control fish in an artificial channel having a water velocity of

1.28 m/s (Scheiwe 1974). Such reduced physical fitness can result in increased vulnerability of prey fish (Bams 1967, Hertig and Witt 1967, Hatfield and Anderson 1972, Sylvester 1972, Coutant 1973, Kania and O'Hara 1974). Emphysema on fish skin may facilitate microbial invasion (Sniesko 1974). Indirect mortality associated with GBT is often mentioned in the literature, but documentation is rare.

Based upon the need for better information on effects of gas supersaturated water on brown and rainbow trout in the Bighorn River, this study was designed to:

(1) determine the relationship between juvenile brown and rainbow trout size and susceptibility to GBT;

(2) compare the relative sensitivity of juvenile brown and rainbow trout to GBT;

(3) evaluate the ability of juvenile brown and rainbow trout to recover from GBT at various levels of severity;

(4) determine the effect of repeated exposure to gas supersaturated water on juvenile brown trout; and

(5) investigate the sublethal effects of exposure to gas supersaturated water on fish growth, predator-prey relationships, and susceptibility to microbial invasion.

METHODS

Gas Supersaturated Water Production and Measurement

This study was conducted in laboratory facilities at the United States Fish and Wildlife Service, Bozeman Fish Technology Center. Gas supersaturated water was produced by a method similar to that described by Bouck and King (1973).

An air compressor was used to force air into a water pipeline. Increased turbulence and pressure forced air into solution (Figure 1). Six 30-d exposure tests were conducted in nine fiberglas tanks (57 cm long, 33 cm deep, 43 cm wide), each subdivided into two equal sections by a wooden frame covered by 400.0 cm^2 of plastic screening. Water depth was 22.0 cm. Equal flow of water was provided through PVC pipe to each side of each tank. Mixing was complete throughout the tank; no gradient of gas levels was present.

Two levels of gas supersaturated water were produced (mean of six tests = 112 ± 1.0% and 125 ± 0.7%) by mixing artificially supersaturated water with 102 - 104% gas supersaturated spring water. Daily monitoring of delta P was accomplished using a Weis saturometer for the control (mean of six tests = 104 ± 1.2%) and Bouck gasometers (Bouck 1982) for the two test treatments; meters were calibrated weekly by taking measurements in a the same treatment tank with both kinds of instruments. Dissolved oxygen (DO) was measured using a YSI dissolved oxygen meter, standardized weekly by Winkler's procedure (APHA 1976). Temperature was was measured in centigrade (C) using a mercury or digital thermometer. Gas measurements were taken daily from one tank of each gas treatment. Daily temperature and dissolved oxygen (DO) measurements were

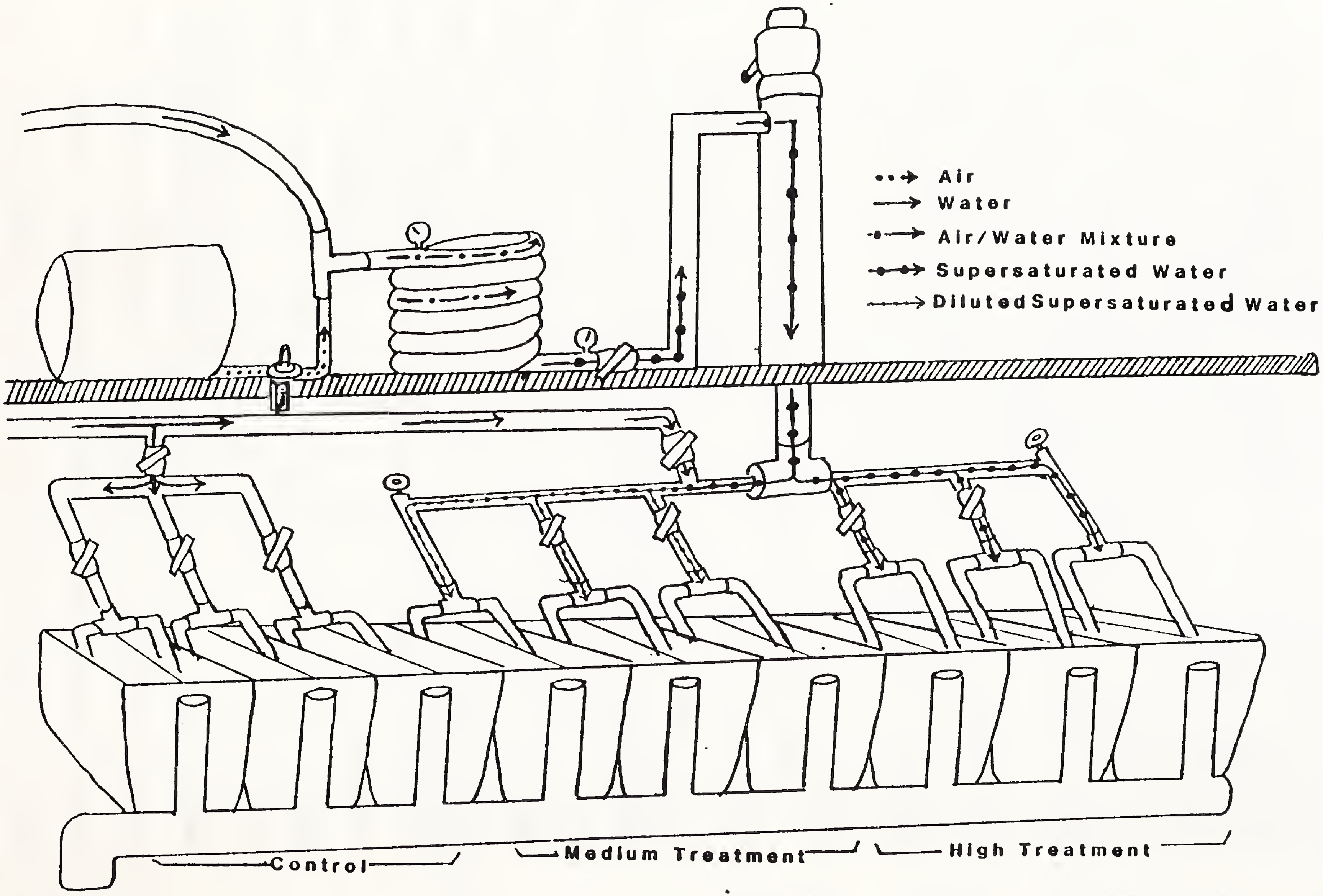

Figure 1. Laboratory apparatus used to test effects of three levels of gas supersaturation on juvenile brown and rainbow trout.

taken on both sides of each tank. A rotation schedule ensured equal distribution of measurements. Barometric pressure was measured daily using a Princo Nova, fortin-type mercury barometer.

Gas levels fluctuated somewhat during the first three tests in the medium gas treatment and during tests 2 and 3 of the high gas treatment. The problem was corrected in subsequent tests by overhauling the measuring equipment and by installing a constant differential pressure regulator on the air compressor (Table 1, Figures 2 - 7).

Table 1. Mean delta P values (mm) for 30-day exposure tests 1 - 6.

Test	Treatment	Delta P values ± SD
1	High	155 ± 6
2	High	153 ± 15
3	High	162 ± 13
4	High	167 ± 6
5	High	160 + 6
6	High	160 ± 9
1	Medium	82 ± 20
2	Medium	78 ± 22
3	Medium	69 ± 15
4	Medium	83 ± 7
5	Medium	72 ± 11
6	Medium	84 ± 7
1	Control	16 ± 2
2	Control	38 ± 3
3	Control	29 ± 4
4	Control	20 ± 3
5	Control	26 ± 8
6	Control	25 ± 5

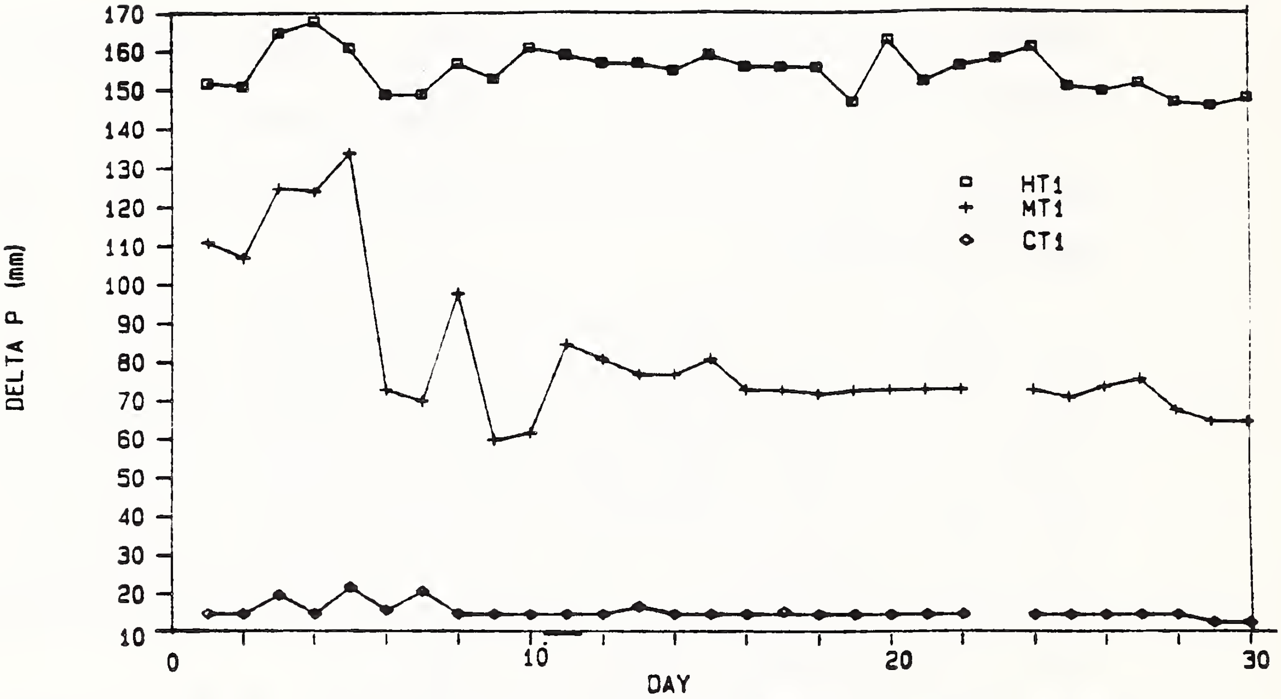

Figure 2. Delta P of water for the high (HT)(mean ^P = 155 mm and mean percent total saturation = 124.3), medium (MT)(mean ^P = 82 mm and mean percent total saturation = 112.8), and control treatments (CT)(mean ^P = 16 mm and mean percent total saturation = 102.5), test 1, March 15-April 15, 1986.

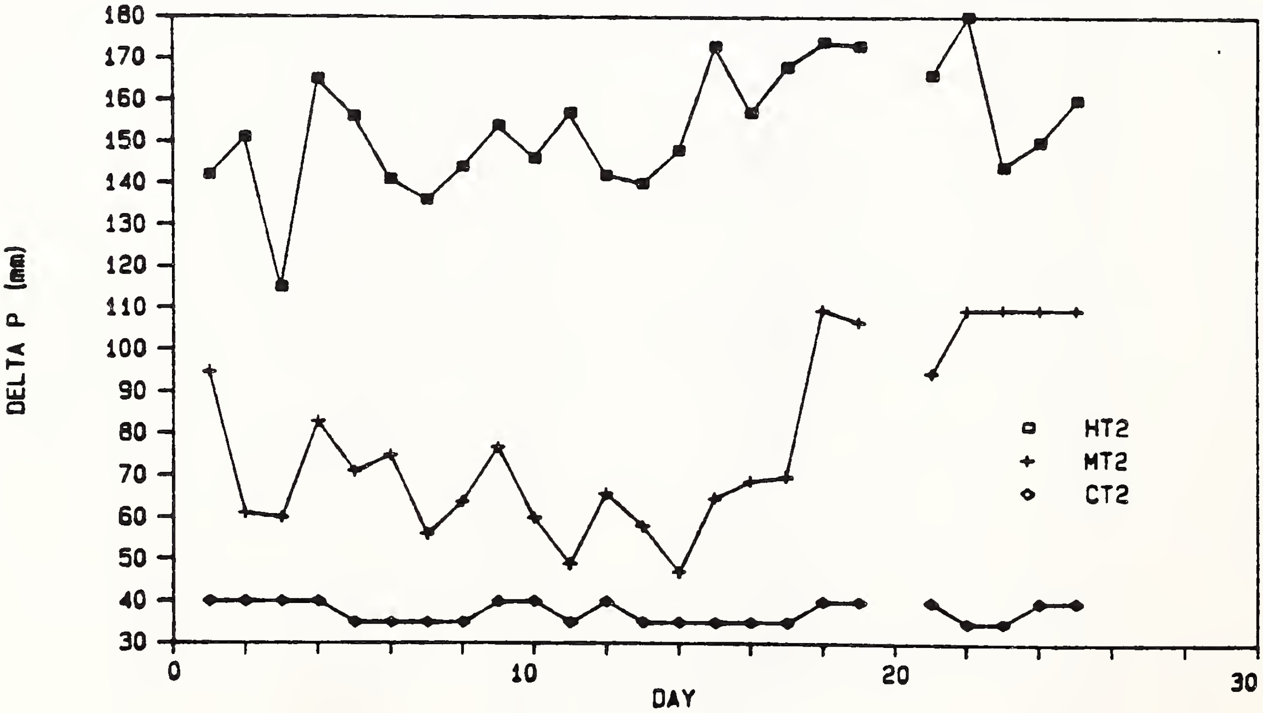

Figure 3. Delta P of water for the high (HT)(mean ^P = 153 mm and mean percent total saturation = 124.0), medium (MT)(mean ^P = 78 mm and mean percent total saturation = 112.3), and control treatments (CT)(mean ^P = 38 mm and mean percent total saturation = 105.9), test 2, May 18-June 11, 1986.

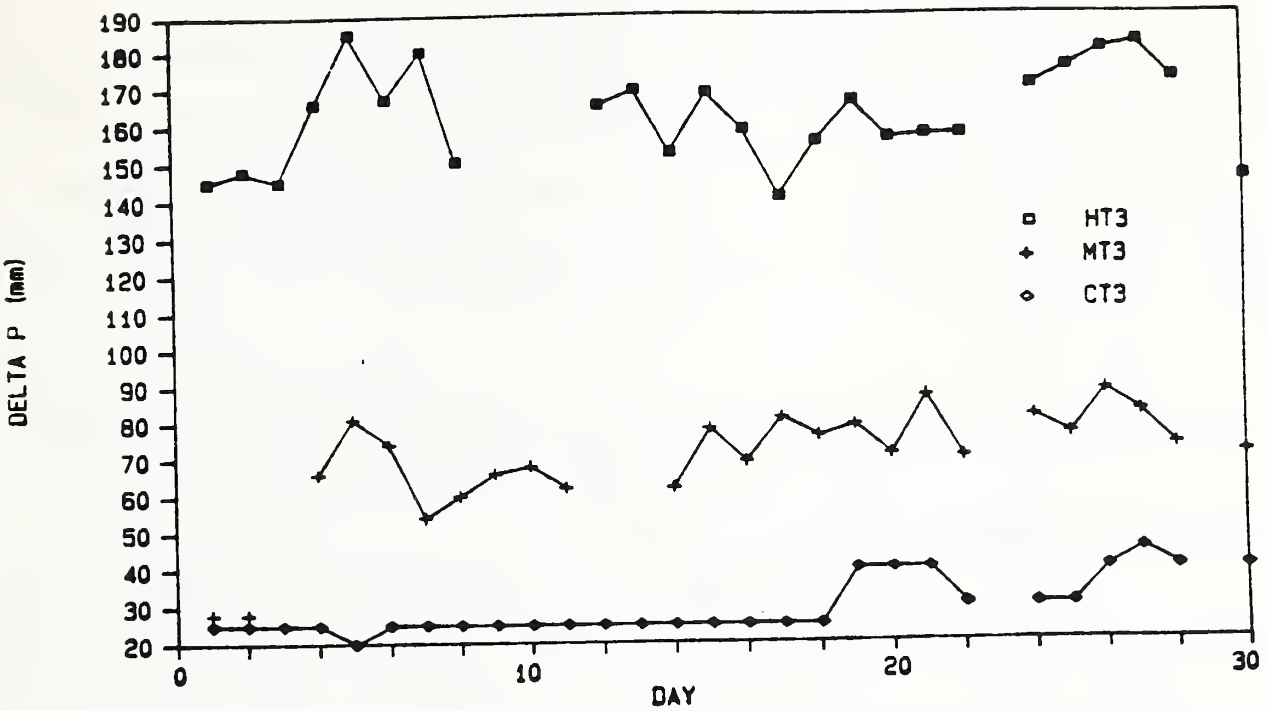

Figure 4. Delta P of water for the high (HT)(mean ^P = 162 mm and mean percent total saturation = 125.4), medium (MT)(mean ^P = 69 mm and mean percent total saturation = 110.8), and control treatments (CT)(mean ^P = 29 mm and mean percent total saturation = 104.5), test 3, July 17-August 17, 1986.

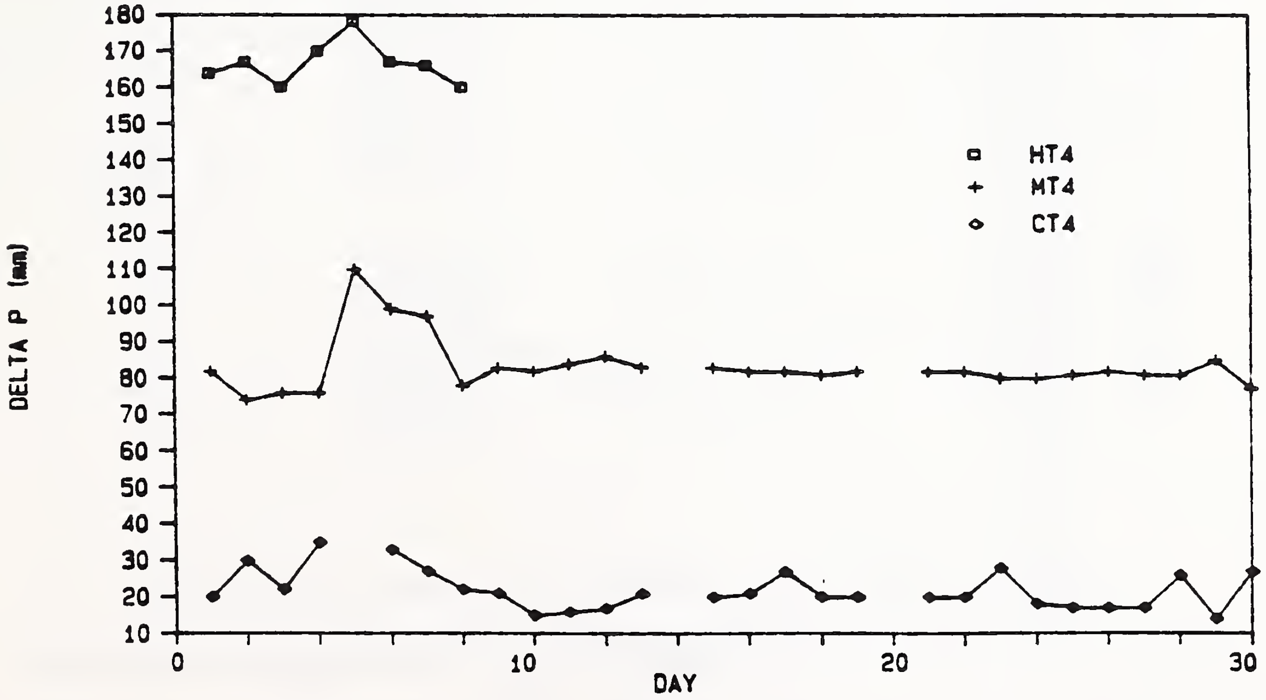

Figure 5. Delta P of water for the high (HT)(mean ^P = 167 mm and mean percent total saturation = 126.1), medium (MT)(mean ^P = 83 mm and mean percent total saturation = 113.0), and control treatments (CT)(mean ^P = 20 mm and mean percent total saturation = 103.3), test 4, September 28-October 29.

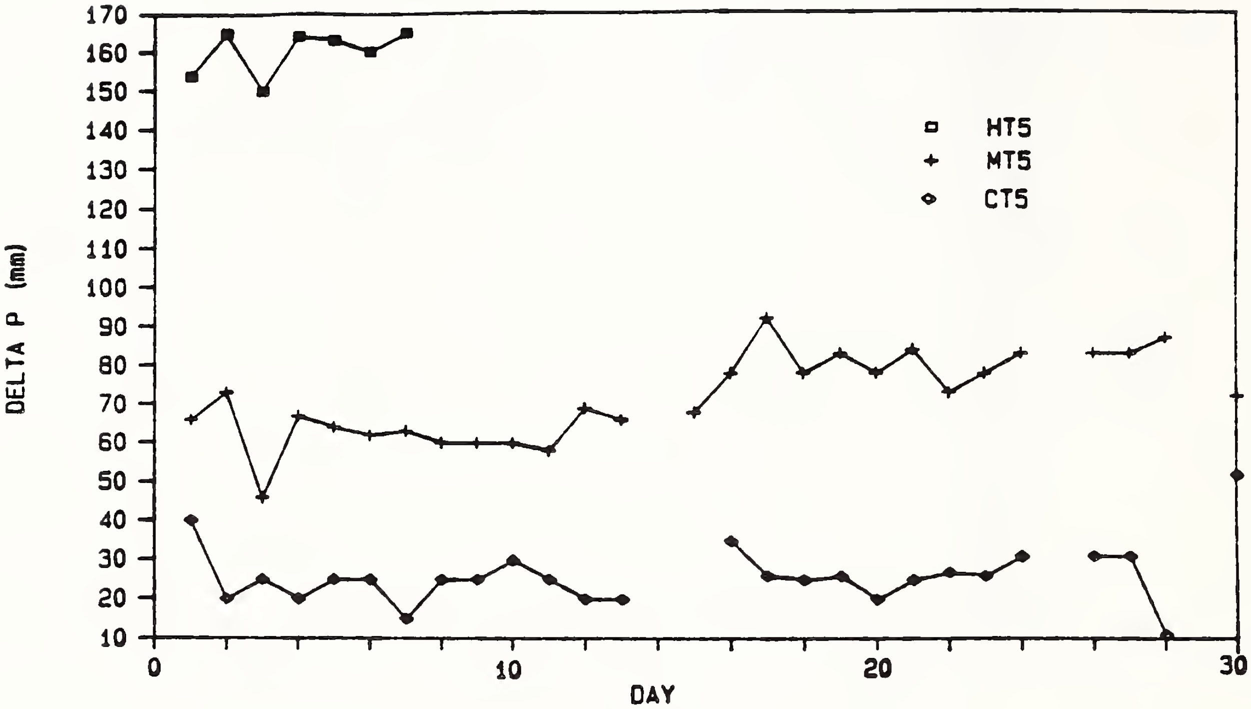

Figure 6. Delta P of water for the high (HT)(mean ^P = 160 mm and mean percent total saturation = 125.0), medium (MT)(mean ^P = 72 mm and mean percent total saturation = 111.2), and control treatments (CT)(mean ^P = 26 mm and mean percent total saturation = 104.1), test 5, January 9-February 9.

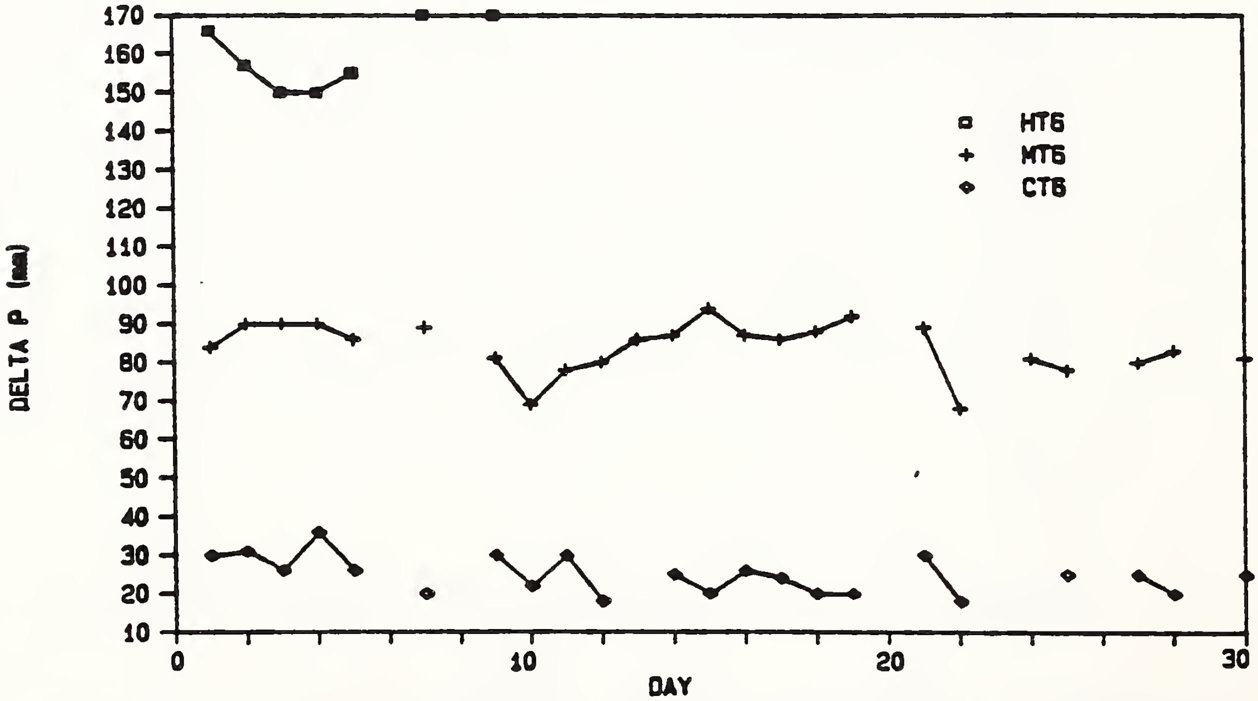

Figure 7. Delta P of water for the high (HT)(mean ^P = 160 mm and mean percent total saturation = 125.1), medium (MT)(mean ^P = 84 mm and mean percent total saturation = 113.2), and control treatments (CT)(mean ^P = 25 mm and mean percent total saturation = 103.9), test 5, February 19-March 19.

Dissolved oxygen concentrations and water temperature were relatively constant between tests except during test 4 when temperature was lower (Table 2). This problem was corrected by increasing the flow of warm spring water into the system.

Table 2. Mean dissolved oxygen concentrations and water temperatures during tests 1-6.

Test	Treatment	Dissolved Oxygen (mg/l)	Temperature (°C)
1	High	10.5 ± 0.4	10.2 ± 0.4
2	High	11.4 ± 0.4	9.7 ± 0.4
3	High	11.3 ± 0.3	9.7 ± 0.3
4	High	11.6 ± 0.4	8.6 ± 0.1
5	High	10.7 ± 0.8	10.4 ± 0.3
6	High	10.6 ± 0.5	11.0 ± 0.1
1	Medium	9.6 ± 0.3	10.2 ± 0.4
2	Medium	10.6 ± 0.4	9.8 ± 0.2
3	Medium	9.9 ± 0.3	10.0 ± 0.2
4	Medium	10.4 ± 0.4	8.1 ± 0.1
5	Medium	9.4 ± 0.3	10.0 ± 0.4
6	Medium	9.5 ± 0.4	10.2 ± 0.5
1	Control	8.9 ± 0.2	10.1 ± 0.2
2	Control	9.6 ± 0.4	10.1 ± 0.5
3	Control	9.2 ± 0.2	10.0 ± 0.2
4	Control	9.4 ± 0.4	7.9 ± 0.1
5	Control	8.6 ± 0.3	9.8 ± 0.3
6	Control	8.8 ± 0.3	9.9 ± 0.6

After each 30-d test, values for daily delta P, DO, water temperature, and barometric pressure were used in the formulas of Colt (1984) to calculate the mean 30-d gas saturation levels.

Fish Care

Brown trout eggs were obtained from wild stock of the Bighorn River in early December, 1985. At the same time, domestic Shasta strain rainbow trout were spawned at the Ennis Fish Hatchery.

Eggs were water hardened, treated with 100 ppm alpha caps-7 betadine and transported to the Bozeman Fish Technology Center where they were incubated in Heath trays supplied with spring water (19.0 L/min at 10±1 °C). Eggs were treated five times each week with a solution of 1:600 100% formalin. Eggs hatched in approximately 30-d. At the end of January, fish were transferred to 1.8 m circular fiberglas tanks supplied with 42 - 49 L/min of 10±1 °C spring water. Fish were fed a diet of Silver Cup Salmon Pellets (Murry Elevators, Murry, UT) of appropriate size. Feed rations were calculated using the formula of Piper et al. (1982) on the first day of feeding and every 30-d thereafter.

Because Bighorn River brown trout were hesitant to feed on pellets or to feed at a predictable rate, the food ration was reduced until brown trout consumed all food offered. Bacterial infection (A gram-negative flagellate identified in September, 1986) was controlled with periodic drip treatments of 11.0 ml/h of hyamine and adding Terramycin to the diet. Growth of fish was controlled by adjusting rearing tank water temperature.

Test Fish Selection

Mean fish length was determined before each experiment by randomly selecting 25 - 100 fish, measuring each to the nearest 1 mm, and returning them to the rearing tanks (Table 3). Fish of each species were then randomly selected from the rearing tanks, weighed, and placed into each experimental tank (Table 4). The number of fish used varied by test because as fish grew the number of fish each tank could support decreased (Table 3). Fish size increased with each test, except rainbow trout used in test 6 were smaller than rainbow trout used in test 5.

Table 3. Pre-exposure mean lengths of juvenile rainbow and brown trout computed using an aggregate of fish from high, medium, and control gas treatments.

Species	Test	Mean total length (mm ± SD)	Number of fish measured
Brown	1	35 *	25
Brown	2	53 *	25
Brown	3	62 ± 6	102
Brown	4	91 ± 8	73
Brown	5	126 ± 6	100
Brown	6	173 ± 12	90
Rainbow	1	34 *	25
Rainbow	2	71 *	25
Rainbow	3	91 ± 11	95
Rainbow	4	131 ± 14	39
Rainbow	5	194 ± 20	100
Rainbow	6	179 ± 14	90

* Data not available for standard deviation calculations

Table 4. Mean weight and number of juvenile rainbow and brown trout exposed to high, medium, and control levels of gas supersaturation during tests 1, 2, 3, 4, 5, and 6.

Species	Exposure test	Gas treatment	Total number of fish exposed	Mean weight (g/fish)
Brown	1	High	150	0.3
Brown	1	Medium	150	0.3
Brown	1	Control	150	0.3
Brown	2	High	75	1.3
Brown	2	Medium	75	1.2
Brown	2	Control	75	1.2
Brown	3	High	75	2.9
Brown	3	Medium	75	2.9
Brown	3	Control	75	2.9
Brown	4	High	75	8.3
Brown	4	Medium	75	8.3
Brown	4	Control	75	7.9
Brown	5	High	45	22.9
Brown	5	Medium	45	23.0
Brown	5	Control	45	21.3
Brown	6	High	30	61.5
Brown	6	Medium	30	59.7
Brown	6	Control	30	59.7
Rainbow	1	High	150	0.4
Rainbow	1	Medium	150	0.4
Rainbow	1	Control	150	0.4
Rainbow	2	High	75	3.4
Rainbow	2	Medium	75	3.6
Rainbow	2	Control	75	3.6
Rainbow	3	High	75	8.9
Rainbow	3	Medium	75	8.4
Rainbow	3	Control	75	8.2
Rainbow	4	High	45	26.3
Rainbow	4	Medium	45	26.7
Rainbow	4	Control	45	26.1
Rainbow	5	High	45	79.3
Rainbow	5	Medium	45	89.5
Rainbow	5	Control	45	83.5
Rainbow	6	High	30	60.5
Rainbow	6	Medium	30	60.3
Rainbow	6	Control	30	57.8

Gas Supersaturation Bioassay Data Analysis

The influence of fish length and weight on susceptibility of juvenile brown and rainbow trout to GBT was evaluated, and relative sensitivity was compared. Percent cumulative mortality was calculated for control, medium, and high treatment fish of both species for all tests.

Where: Percent Cumulative Mortality =

$$\frac{(\text{Mortality at day } x) + (\text{Mortality at day } x+1) + (\text{Mortality at day } x_n)}{\text{Fish number at day } 0}$$

multiplied x 100

Significant differences in mortality were tested by comparing mortality of control fish to mortality of medium and high gas treatment fish using Biomedical Data processing (BMDP) software (Dixon et al. 1983). BMDP employs the non-parametric Breslow rank test to generate p-values. The effect of size on susceptibility to GBT was then determined by comparing intraspecific percent cumulative mortality from the high treatment of the six tests (Table 5). Relative sensitivity of juvenile brown and rainbow trout was compared by testing for significant difference in percent cumulative mortality between high treatment rainbow and brown $\overset{n}{\text{trout}}$ of similar size (Table 5).

Table 5. Intra- and interspecific mortality comparisons for juvenile brown (BT) and rainbow trout (RBT) exposed to the high gas treatment during tests 1 - 6.

Brown trout mortality comparison	Rainbow trout mortality comparison	Interspecific mortality comparison
BT1 vs BT2	RBT1 vs RBT2	BT1 vs RBT1
BT2 vs BT3	RBT2 vs RBT3	BT3 vs RBT2
BT3 vs BT4	RBT3 vs RBT4	BT4 vs RBT3
BT4 vs BT5	RBT4 vs RBT6	BT5 vs RBT4
BT5 vs BT6	RBT6 vs RBT5	BT6 vs RBT6

Evaluation of External Symptoms of GBT

Each juvenile brown and rainbow trout that died in the high treatment of experiments 1 - 4 was examined for external symptoms of GBT to determine the relationship between fish size and body region of GBT occurrence. All symptoms were recorded in detail during these tests. Surviving juvenile brown and rainbow trout of the medium treatment from tests 3, 4, 5, and 6 were examined to compare the frequency of external symptom difference between the two species.

Recovery Tests

A different gas supersaturating system was developed for recovery studies (Figure 8). Both rainbow and brown trout were placed into two, 4-m diameter tanks and exposed to 118% supersaturated water for 120-h, the approximate time it took for external symptoms to appear.

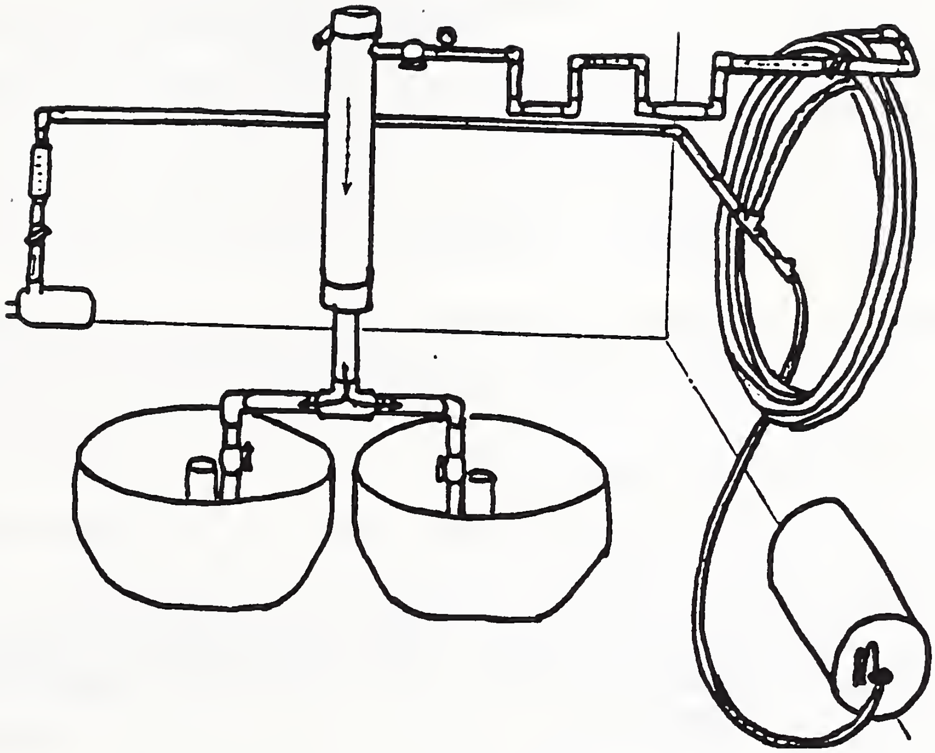

Figure 8. Laboratory apparatus used to produce gas bubble trauma in juvenile brown and rainbow trout for recovery tests.

Affected fish were removed from treatment tanks, symptoms recorded, and each fish was assigned a status rating of 0, 1, 2, or 3 (Table 6). Fish were then transferred to 104% supersaturated water and recovery was monitored every other day for 30-d.

A second series of recovery tests was conducted to investigate the effects of repeated exposure of juvenile brown and rainbow trout to gas supersaturated water. The procedure was identical to other recovery tests except fish were exposed initially, survivors were given 30-d to recover, and then were exposed a second and third time, with a 30-d recovery period in between. One additional GBT rating (4) was used in this part of the study to describe fish that did not survive repeat exposure to gas supersaturated water (Table 6). Fisher's Exact Test (Hintze 1987) was used to test for changes in symptom severity between exposures.

Table 6. Gas bubble trauma description and other criteria used to rank laboratory recovery data.

Description and Status	Rating
-No visible external symptoms. Fish have developed no external symptoms of GBT during exposure to gas supersaturated water or have lost all previously acquired symptoms during recovery....................................	0
-Emphysema present in one to four of the following regions: Buccal cavity, mandible, maxillary, left opercle, right opercle, left eye, right eye, head, left lateral line, right lateral line, left pectoral fin, right pectoral fin, anal fin, adipose fin, caudal fin, trunk. Fish may display minor stress.......	1
-Emphysema present on more than four of the above regions. Mild exopthalmia in one or both eyes, but no evidence of impaired swimming. Impaired vision combined with reduced appetite may reduce feeding activity and lead to poor nutritional status.............	2
-Severe emphysema and exopthalmia in one or both eyes. Eyes may be cloudy and hemorrhaging. May lack response to visual stimuli. Noticeable swimming impairment. Obvious loss of equilibrium, spastic swimming may be evident. Blinded fish physiologically deteriorate (embedded scales and weight loss) and may starve. Acute mortality is possible in some cases.......	3
-Fish that died during the second or third exposure to gas supersaturated water............	4

Growth of Fish Exposed to Sublethal Levels of Gas Supersaturation

Brown and rainbow trout juveniles from control and medium gas treatment tests 1, 3, 5, and 6 were used to determine the effect of exposure to sublethal levels of gas supersaturation on fish growth. Weights of juvenile brown and rainbow trout from any high treatment or from medium treatments of tests 2 and 4 were not used to test for sublethal effects on growth because mortality attributable to GBT occurred in these tests.

Growth effects were examined by comparing control fish weight to treatment fish weight. Fish weights taken on days 1 and 30 from tests 1, 3, 5, and 6 were pooled to provided a sample size of twelve mean weights (four tests @ three replicates/test) (Table 7). Average day 1 and 30 control and medium treatment weights were calculated using these 12 weights and a comparisons were made using the Man-Whitney nonparametric rank test (Hintze 1987).

Table 7. Sample sizes used to test for the effects of gas supersaturated water on juvenile brown (BT) and rainbow trout (RBT) growth.

Test	Treatment	Number of samples weighed/treatment	Number of fish weighed/sample			
			BTDAY1[a]	BTDAY30[b]	RBTDAY1[c]	RBTDAY[d]
1	Control	3	150	139	150	145
3	Control	3	75	73	75	71
5	Control	3	45	45	30	28
6	Control	3	30	29	30	26
1	Medium	3	150	140	150	145
3	Medium	3	75	66	75	69
5	Medium	3	45	45	30	27
6	Medium	3	30	30	30	30

a = Brown trout weighed on day 1 b = Brown trout weighed on day 30
c = Rainbow trout weighed on day 1 d = Rainbow trout weighed on day 30

Predation Susceptibility

Tank Tests:

Sublethal effects of GBT on juvenile brown and rainbow trout were evaluated during predation susceptibility tests similar to those described by Bams (1967). The experimental procedure (Figure 9) was repeated 14 times.

One hour prior to each test, eight Arlee hatchery rainbow trout ranging in size from 200-270 mm (four during the first four tests) were transferred from a 1.8 m circular fiberglass rearing tank (80 cm deep) to three replicate 1.2 m tanks (65 cm deep). Each tank was supplied with a constant flow of water which exited via a single stand-pipe. Different prey fish were used during

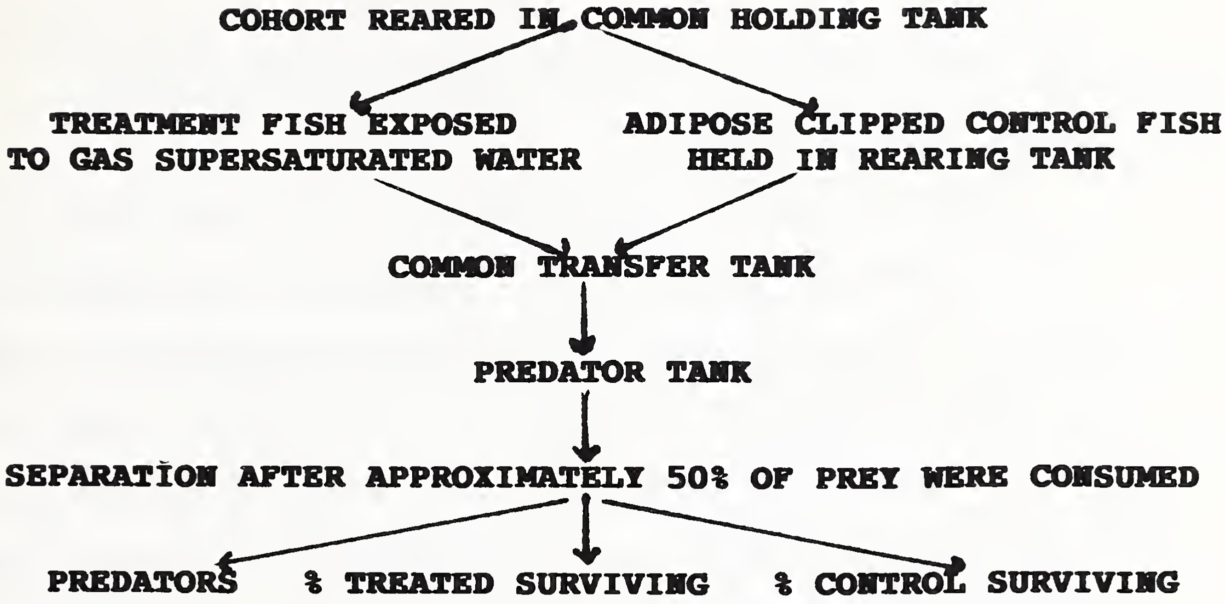
COHORT REARED IN COMMON HOLDING TANK
TREATMENT FISH EXPOSED TO GAS SUPERSATURATED WATER
ADIPOSE CLIPPED CONTROL FISH HELD IN REARING TANK
COMMON TRANSFER TANK
PREDATOR TANK
SEPARATION AFTER APPROXIMATELY 50% OF PREY WERE CONSUMED
PREDATORS
% TREATED SURVIVING
% CONTROL SURVIVING

Figure 9. Flow diagram for tests to determine relative vulnerability to predation between fish exposed to gas supersaturated water and unexposed fish.

each test. Juvenile rainbow (mean length = 46 ± 8 mm) and brown trout (mean length = 42 ± 4 mm) that had survived exposure to 124% supersaturated water for 30-d were used during the first four tests. Larger rainbow (mean length = 77 ± 6 mm) and brown trout (mean length = 56 ± 7 mm) that had been exposed for 30-d to 112% supersaturated water were used for the second four tests. Brown trout exposed for 30-d to 110 % were used for two tests. Brown trout exposed 13 hours to 130% supersaturated water were used during the remaining four tests.

Three days prior to predator avoidance tests, numbers of control fish equal to numbers of experimental fish were adipose clipped. Bams (1967) found that fin clipping control fish created no bias in testing. Control fish were from the same cohort, fed the same food, and reared at the same water temperature, but had not been exposed to supersaturated water.

Prey (25 control and 25 test) were placed in a 4 L plastic bowl and gently stirred into the predator occupied water. When predators had ingested approximately 50% of the prey, they were removed from the tanks. Test results were discarded if more than 35 or less than 15 prey remained; five tests were invalidated. Surviving prey were counted, measured, and sorted according to experimental history. Instantaneous mortality ratios (Bams 1967) were calculated using the following equation:

$$dp = \frac{-\log_e (i1)}{-\log_e (i2)}$$

where:
dp = instantaneous mortality ratio
i1 = surviving treatment fish/starting # of treatment fish
i2 = surviving control fish/ starting # of control fish

When the instantaneous mortality rate of fish exposed to gas supersaturated water is greater than the instantaneous mortality rate of control fish, dp will be greater than 1. When the predation ratio is equal, dp = 1. The chi-square correction for continuity (Zar 1984) was used to test for statistical significance.

Experimental Stream Tests:

Seven predation tests were conducted in an experimental stream to determine if juvenile rainbow and brown trout exposed to high gas supersaturation levels are more susceptible to predation than non-exposed fish.
The rectangular study section within an oval experimental stream channel was 5.1 m long, 0.6 m wide, 0.4 m deep, with a water depth of 0.39 m (Figure 10). Plastic-mesh screening formed upstream and downstream boundaries and metal screening placed on top of the channel kept fish from jumping out. Gravel (mean diameter = 1.9 cm) 0.3 m deep, substrate was used to try to simulate natural conditions. The stream channel was provided with 8 L/min of 16.6 ^{o}C water containing 6.2 ppm DO. Water depth was regulated at 39.0 cm by a single stand pipe. A Sears electric outboard motor (with 30 pounds thrust) created a mean stream velocity of 7 cm/sec. The thalweg of the section was partially directed using a 42.0 cm long, 10.0 cm wide, and 2.0 cm deep wing-deflector located at the upstream end of the channel. Three types of escape cover were provided for the prey (Figure 10). Two trapezoidal wooden slabs (30.0 cm x 21.0 cm x 4.0 cm x 10.5 cm and 33.5 cm x 26.0 cm x 4.0 cm x 9.0 cm) furnished overhead cover, while a straight white plastic cylinder (37.5 cm long,6.0 cm diameter) and an elbowed white plastic cylinder (22.0 cm long,6.5 cm diameter) provided tunnel-type cover.

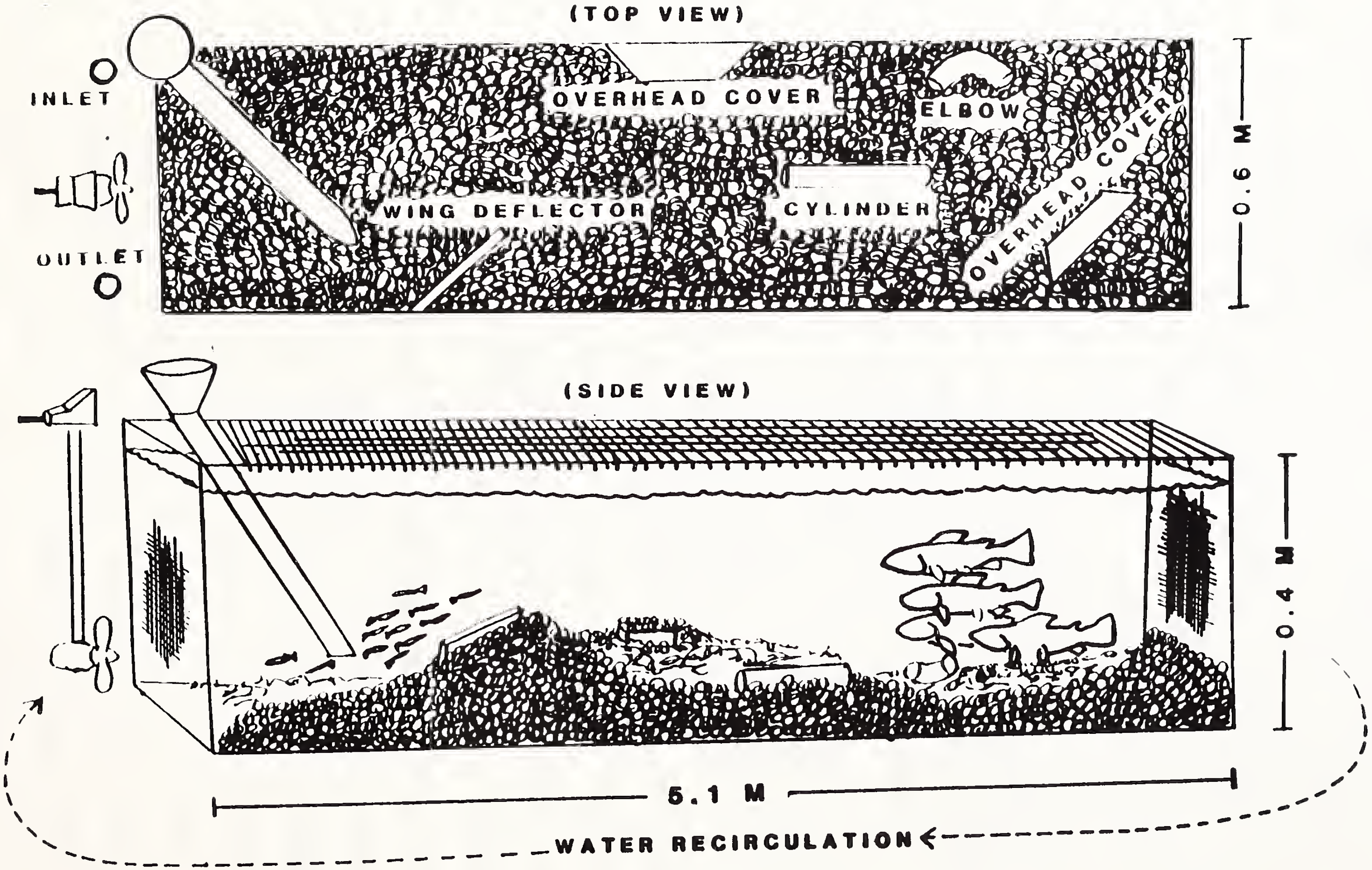

Figure 3. Experimental stream used in the second series of predation tests May 1 - 21, 1987.

The experimental procedure for the seven experimental stream tests was similar to that of tank tests except treatment fish with external symptoms of GBT were selected over those without external symptoms and predators were maintained in the channel between tests. The predators (four Arlee hatchery rainbow trout) ranged in size from 270-286 mm total length. Different prey fish were used during each test. An equal number of treatment prey and control prey (except during rainbow test 2 when 14 treatment and 15 control fish were used) were placed in a 10 L bucket. The electric outboard motor was turned on, and prey were introduced into the channel through a funnel located in the upstream portion of study section (Figure 10). An observer watched the predators consume prey from behind a black curtain until approximately one-half the prey were consumed. This time ranged from 34 min 47 sec to 88 min 54 sec. The predators were then removed and surviving prey were captured, separated into treatment and control groups, and measured. Because there stream tests were not repeated, Fisher's exact test (Hintze 1987) was used to test for significant difference in predation on treatment and control fish.

Juveniles brown trout (mean total length = 46 ± 3 mm) were used as prey fish in the first five tests. Gas bubble trauma symptoms were induced in prey fish by exposure to 118% gas supersaturated water for 4 - 7-d; control prey were not exposed to gas supersaturated conditions. Control fish were marked with an adipose clip 1-h prior to testing. Fish showing external symptoms of GBT were intentionally selected. All fish captured (up to five fish per dip including fish without external signs of GBT) were placed in a container with control fish until 25 treatment prey were obtained.

Two tests were conducted using rainbow trout (mean total length 60 ± 6 mm) as prey. One-half of the treatment rainbow trout prey in the first test had external symptoms of GBT induced by exposure to 118% gas supersaturation and the remaining 12 fish were randomly sampled from the exposure tank. During the second test the water level in exposure tank 1 wa held at 10 cm and the water level in exposure tank 2 was raised to 45 cm (Figure 11). For a period of 4-d all fish in tank 1 were examined for external signs of GBT. Those with external signs were transferred to tank 2 to allow for compensation, but not recovery. Fourteen rainbow trout prey with external signs of GBT were obtained in this manner.

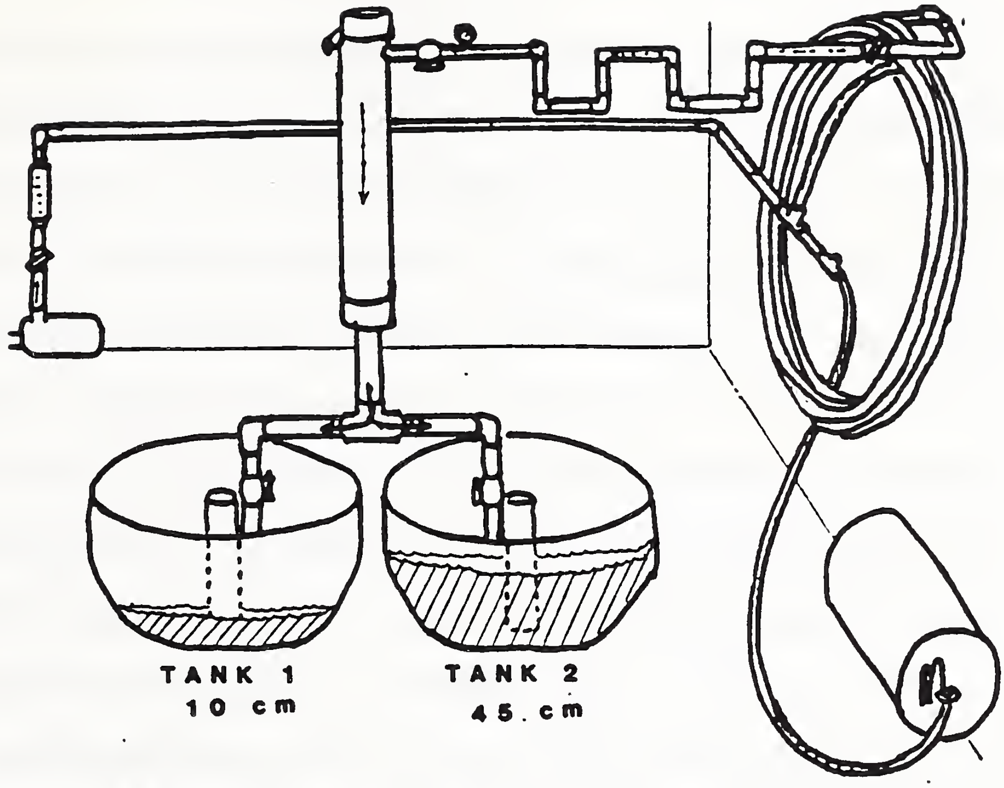

Figure 11. Apparatus and water level system used to induce external symptoms of GBT in rainbow trout for predation tests May 16 - 21, 1987.

Bacterial Challenge

The effects of GBT on the susceptibility of juvenile rainbow and brown trout to the pathogen Aeromonas hydrophila was tested. A. hydrophila CDC Strain III A-20 was obtained from the Wyoming Department of Game and Fish, Laramie, WY. Test protocol involved: 1) antiserum production; 2) pre-treatment serial dilution; 3) challenge application; 4) post-treatment serial dilution; 5) fluorescent antibody technique application; 6) enumeration and statistical analysis of bacterial infection of the kidney using a two sample T-test (Hintze 1987).

Preparation of the antigen was completed using the method of Garvey et al. (1977). Five hundred milliliters of Tripticate Soy Broth (TSB) were inoculated with broth culture of A. hydrophila that had incubated at 28 °C for 18-h. At the end of the incubation period, an equal volume of 0.6% formalinized saline was added. This preparation was stored at room temperature for 4-d. Sterility of the bacterial suspension was checked by inoculating a plate of Triptic Soy Agar (TSA), incubating for 48-h at 28 °C, and examining the plate for growth.

Bacteria were collected using centrifugation at approximately 3000 rpm for 0.5-h. The supernatant fluid was discarded and the bacteria resuspended in 100 ml of 0.85% saline. At 4-d intervals a 2.5 kg rabbit was intravenously injected with 0.5, 1.0, 2.0, 3.0, 4.0, 6.0, and 6.0 ml of the A. hydrophila antigen preparation diluted 50% with physiological saline. The rabbit was rested for 6-d after the last injection. A small serum sample was then obtained by venous puncture and its titer was tested by the agglutination reaction. Specificity of the antiserum was confirmed by testing it against A. salmonicida and Yersinia ruckeri. The rabbit was bled at 3-week intervals. Whole blood was centrifuged at 3000 rpm for 15 min and the serum was removed with a syringe. The antiserum was preserved with 0.2% sodium azide and frozen.

Inoculum was prepared independently for two replicate challenges. Seventy-two hours prior to the challenge a brown trout (approximately 180 mm) was injected with 1.0 cc of a 1.0 x 10^8 suspension of A. hydrophila and placed in 20 °C water. Mortality occurred within 24-h. The kidney of the dead fish was punctured with an inoculating loop which was then used to inoculate a test tube of TSB. The TSB was incubated at 20 °C for 24-h. One tenth milliliter of this suspension was used to inoculate 200 ml of TSB which was then incubated at 37 °C for 12-h.

A pre-treatment serial dilution was made in triplicate to determine the viability of challenge inoculum. One-tenth milliliter of the 12-h challenge inoculum of A. hydrophila was pipetted into 9.9 ml of distilled water to give 1:10^2 dilution. One milliliter of this suspension was transferred to a second test tube containing 9.0 ml of distilled water to give 1:10^3 dilution. This procedure was followed for three more suspensions until a tube with a dilution factor of 1:10^6 was achieved. One hundred microliters of the 1:10^6 dilution were pipetted onto petri dishes containing TSA and incubated at 20 °C for 48-h. Colonies were counted after incubation to verify inoculum viability and to insure that there were approximately 1.1 x 10.0^8 viable cells in the challenge inoculum.

Six juvenile brown trout (180 - 210 mm) were placed in each of five plastic buckets containing 10.0 L f 15.9 °C water with 7.4 mg/L DO. Three fish in each bucket had GBT as a result of exposure to 118% gas supersaturated water for 120-h with no recovery time. The remaining three fish had no previous exposure to gas supersaturated water. Nine milliliters of 12-h challenge inoculum of A. hydrophila were introduced into four of the buckets. The fifth bucket was treated with 9.0 ml of sterile TSB. The challenge times ranged from 10 - 40 min. After the challenge was complete, fish from each bucket were placed into a separate tank that received 2.4 L/min of 15.9 ^{o}C water with 7.6 mg/L oxygen. The negative control treatment was removed at 20 min.

After 96-h fish in each bucket were euthanized with MS-222 and refrigerated at 0 ^{o}C. Fish were measured and weighed, and kidneys were removed and homogenized in 5 ml of distilled water using a tissue homogenizer. One milliliter of homogenized solution was pipetted onto a circle (d = 1.5 cm) on a fluorescent antibody technique slide and heat fixed. This procedure was followed once for each of the 30 fish. One-tenth milliliter of rabbit antiserum was then applied to the slide for 1-h, then rinsed with physiological saline. Commercially prepared fluoroscein-conjugated goat antisera to rabbit immunoglobins was applied to the slide for 0.5-h and then rinsed off with physiological saline.

A fluorescent phase contrast microscope (400x objective) was used to count all bacteria in the circle of each slide. The number of bacteria counted on control and treatment slides were compared using the two sample t-test (Hintze 1987).

RESULTS AND DISCUSSION

Brown and Rainbow Trout Mortality

Significant mortality of medium treatment fish in the 30-d bioassaysoccurred only during tests 2 and 4 (Table 8). No brown trout mortality occurred in control or medium treatments during tests 5 or 6 and no rainbow trout mortality occurred in test 5.

Table 8. Breslow rank analysis of medium gas treatment percent cumulative mortality for juvenile brown (BT) and rainbow trout (RBT) during tests 1, 2, 3, 4, 5, and 6.

Mortality Comparison: Control treatment Species	Control treatment Test	outcome	Medium treatment Species	Medium treatment Test	p-value
BT	1	=	BT	1	0.6287
BT	2	<	BT	2	< 0.0001*
BT	3	=	BT	3	0.1583
BT	4	<	BT	4	< 0.0001*
BT	5	=	BT	5	-------
BT	6	=	BT	6	-------
RBT	1	=	RBT	1	0.3999
RBT	2	<	RBT	2	< 0.0001*
RBT	3	=	RBT	3	0.3173
RBT	4	<	RBT	4	0.0351
RBT	5	=	RBT	5	-------
RBT	6	=	RBT	6	0.3255

* Statistically different at alpha = 0.05

Approximately 30% of mortality in test 2 occurred when delta P values were higher than planned for 10-d (Figure 12). During test 4, all mortality of both species in the medium treatment coincided with a 3-d period of elevated delta P values (Figure 13).

Research has shown that critical levels of gas supersaturation exist for different species of fish (Weitkamp and Katz 1980). The critical level is defined as the maximum level of supersaturation that allows for survival and propagation of aquatic biota. Cutthroat, rainbow, and steelhead trout fry (9.5 cm) were tolerant to water containing 110% saturation of nitrogen, but died when exposed to 115% nitrogen supersaturation (Rucker and Hodgeboom 1953). Juvenile steelhead (180-200 mm) survived exposure to 115% gas supersaturation, but 120% supersaturation caused 100% mortality (Stroud and Nebeker 1976). Apparently a tolerance threshold for juvenile steelhead trout (180 -200 mm) exists between 115 and 120% supersaturation. Data from my study indicate a similar threshold exists for juvenile brown and rainbow trout.

Critical levels of gas supersaturation for brown and rainbow trout were surpassed during tests 2 and 4. The critical threshold required to cause acute mortality in juvenile rainbow and brown trout (53. -131 mm) appears to be between 113-117%. Medium treatment levels never

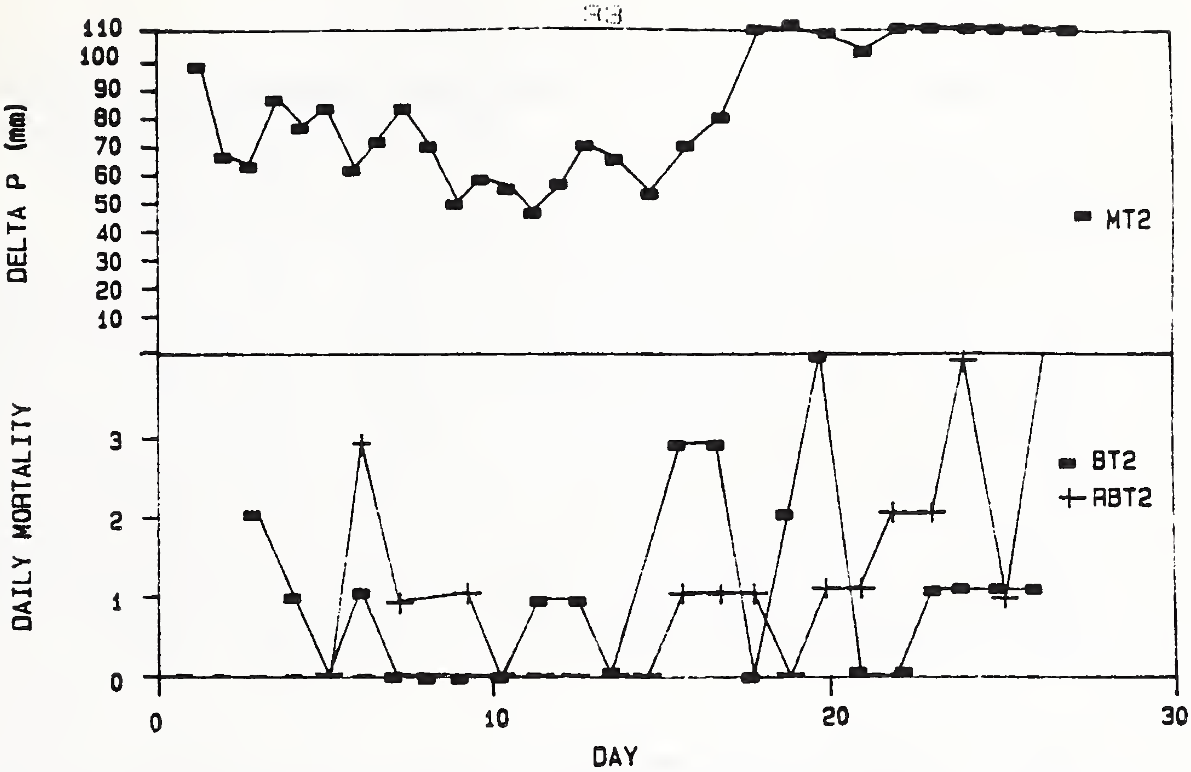

Figure 12. Comparison of medium treatment (MT) juvenile brown (BT) and rainbow trout (RBT) daily mortality and associated ^P values by day during test 2, May 18 - June 11, 1986.

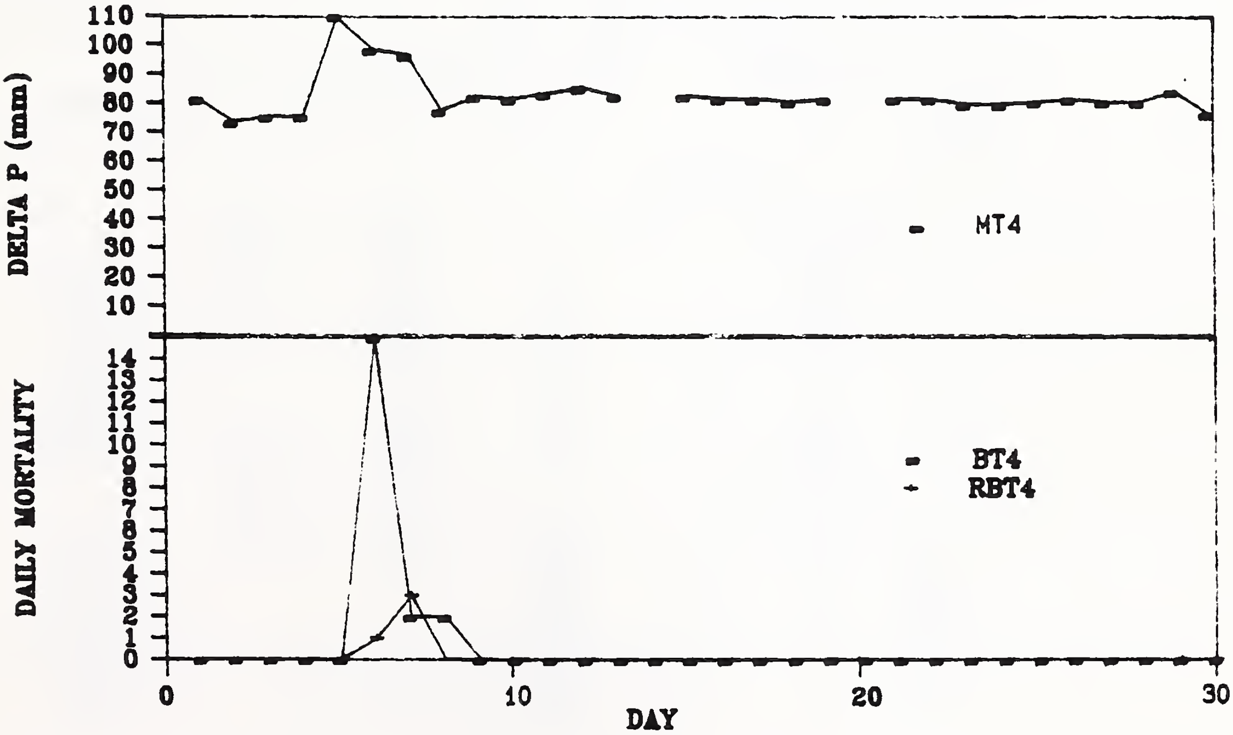

Figure 13. Comparison of medium treatment (MT) juvenile brown (BT) and rainbow trout (RBT) daily mortality and associated ^P values by day during test 4, September 28 - October 29, 1986.

exceeded the critical threshold long enough to cause mortality in tests 1, 3, 5, and 6. Therefore, no statistically significant mortality occurred.

Mortality of rainbow and brown trout of the high gas treatment was significantly greater than that of control fish in all cases except for test 1 rainbow trout (Table 9). Several test 1 control treatment rainbow trout fry died and high treatment rainbow trout mortality was low. The relevance of these data is discussed later.

Table 9. Breslow rank analysis of medium gas treatment percent cumulative mortality for juvenile brown (BT) and rainbow trout (RBT) during tests 1, 2, 3, 4, 5, and 6.

Mortality Comparison					
Control treatment			Medium treatment		p-value
species	test	outcome	species	test	
BT	1	<	BT	1	< 0.0001*
BT	2	<	BT	2	< 0.0001*
BT	3	<	BT	3	< 0.0001*
BT	4	<	BT	4	< 0.0001*
BT	5	<	BT	5	< 0.0001*
BT	6	<	BT	6	< 0.0001*
RBT	1	=	RBT	1	0.7760
RBT	2	<	RBT	2	< 0.0001*
RBT	3	<	RBT	3	< 0.0001*
RBT	4	<	RBT	4	< 0.0001*
RBT	5	<	RBT	5	< 0.0001*
RBT	6	<	RBT	6	< 0.0001*

* Statistically different at alpha = 0.05

Influence of Length and Weight on Susceptibility to GBT

Length and weight of juvenile brown and rainbow trout had a significant influence on susceptibility to supersaturated water. During test 1 percent cumulative mortality for both species exposed to the high gas treatment was significantly less for small fish than for large fish However, there was no statistical difference in brown trout mortality between tests 4 and 5 or rainbow trout mortality between tests 4 and 6.

Table 10. Breslow rank analysis of high gas treatment percent cumulative mortality for juvenile brown and rainbow trout exposed to the high gas treatment during tests 1, 2, 3, 4, 5, and 6.

Mortality comparison outcome	p-value
BT1 < BT2	< 0.0001*
BT2 < BT3	< 0.0001*
BT3 < BT4	< 0.0001*
BT4 = BT5	0.7009
BT5 < BT6	0.0019*
RBT1 < RBT2	< 0.0001*
RBT2 < RBT3	< 0.0001*
RBT3 < RBT4	< 0.0001*
RBT4 = RBT6	0.1778
RBT6 < RBT5	0.0295*

* Statistically different at alpha = 0.05

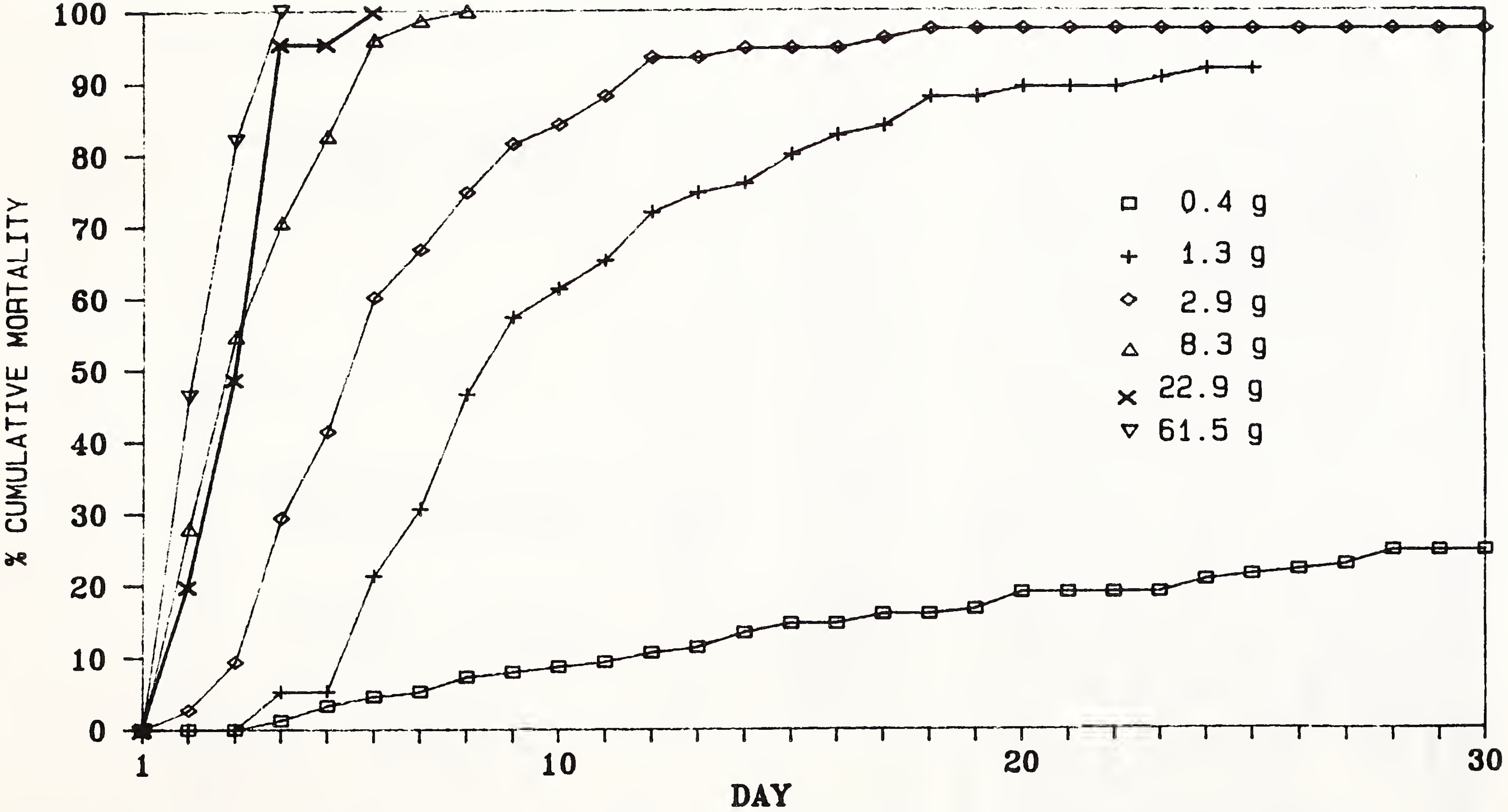

Figure 14. High treatment (125%) juvenile brown trout percent cumulative mortality by day, during tests 1, 2, 3, 4, 5, and 6 (BT1 = 35.2 mm and 0.4 g, BT2 = 53.1 mm and 1.3 g, BT3 = 62.2 mm and 2.9 g, BT4 = 90.7 mm and 8.3 g, BT5 = 126.3 mm and 22.9 g, BT6 = 172.8 mm and 61.5 g).

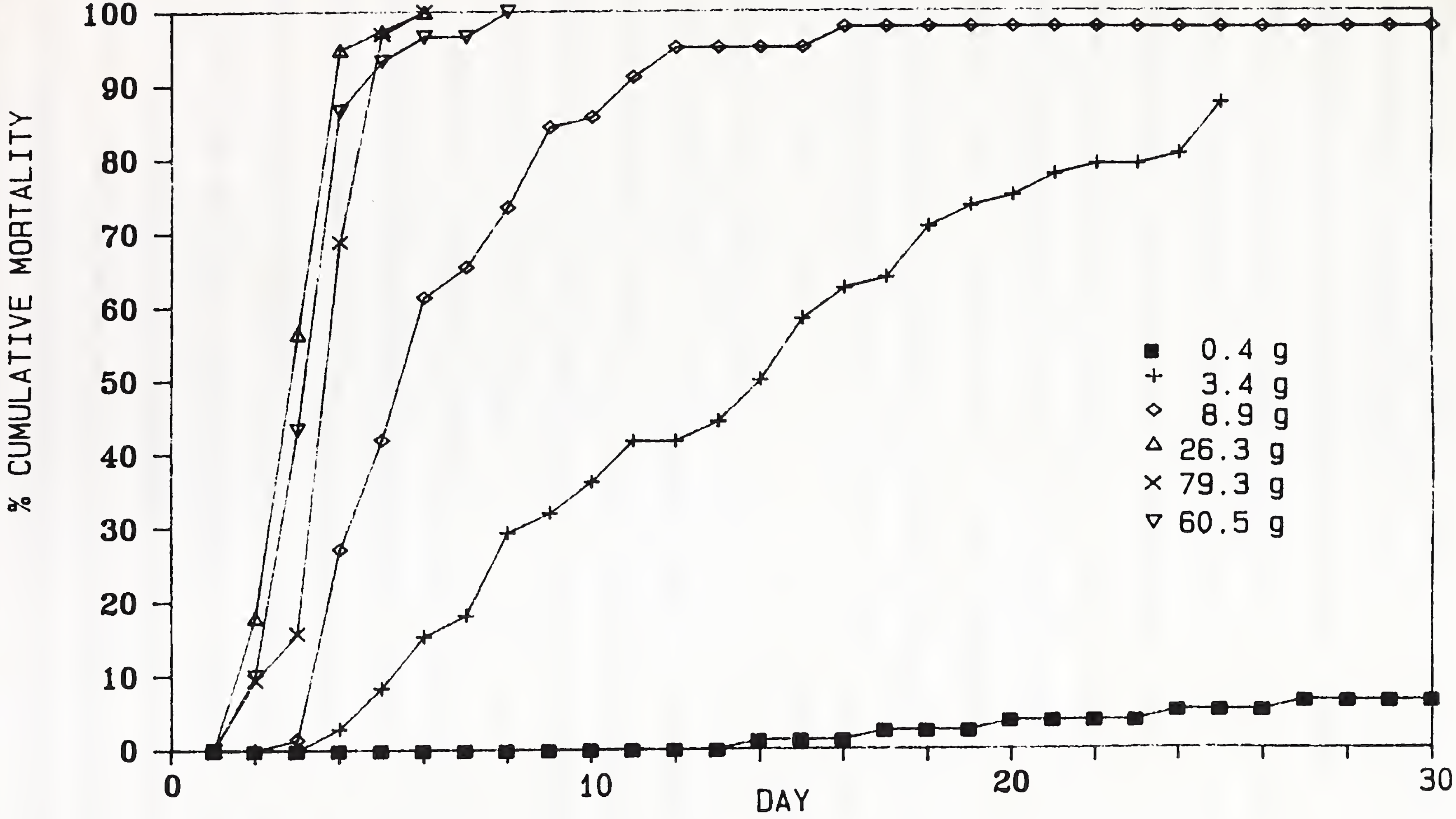

Figure 15. High treatment (125%) juvenile rainbow trout percent cumulative mortality by day, during tests 1, 2, 3, 4, 5, and 6 (RBT1 = 34.0 mm and 0.4 g, RBT2 = 70.5 mm and 3.4 g, RBT3 = 90.6 mm and 8.9 g, RBT4 = 130.5 mm and 26.3 g, RBT5 = 194.1 mm and 79.3 g, RBT6 = 178.7 mm and 60.5 g)

Available literature indicates that fish become more sensitive to gas supersaturated water as they increase in size. Meekin and Turner (1974) found large juvenile chinook salmon exposed to 124% supersaturation suffered greater mortality than did smaller fish of these species. Rucker (1976) tested two size groups of coho salmon (3.8 - 6.0 cm and 8.0 - 10.0 cm) in 119% gas supersaturated water and concluded that larger fingerlings were more subject to harm than smaller fish. Jensen et al. (1986) predicted that larger anadromous juvenile salmonids should be more sensitive to effects of gas supersaturated water than are smaller fish.

The basis for increased susceptibility to gas supersaturated water with size remains unclear. The mechanics of bubble formation (emboli) may offer an explanation for increasing sensitivity to gas supersaturated water with increasing fish size. Harvey et al. (1944) explained the mechanism of emboli formation in the blood stream of vertebrates. Undissolved gases in the blood stream begin to form emboli when they adhere to "nucleation sites" (rough or irregular regions in the vascular system or body tissue). As the delta P of the blood increases, the radius of a gas bubble on the nucleation site expands as gas diffuses into it. If supersaturated conditions continue long enough at a high enough level the buoyant force of the bubble becomes sufficient for it to dislodge from the nucleation site.

Fidler (1985) hypothesized that increased susceptibility is closely associated to the radius and number of nucleation sites in a fish. Two reasons were given as support for this hypothesis. The gas level threshold required for bubble formation is lower for large nucleation sites. Consequently, smaller fish (with smaller nucleations sites) would suffer less severe emboli formation than a larger fish at a given percent TGP. Secondly, larger fish may have greater discontinuity in tissue and vascular wall structure. This may provided a greater number of nucleation sites and result in more emboli.

My results generally support Fidler,s (1985) theory with results of test 4 being the only exception. Total gas pressure was 1% higher during test 4 than in any other test and may have influenced mortality.

External symptoms of GBT in fishes have been thoroughly described (Woodbury 1941, Renfro 1963, Beiningen and Ebel 1970, Harvey 1975, Dawley et al. 1976, Nebeker and Brett 1976, Stroud and Nebeker 1976, Thorn et al. 1978, and Weitkamp and Katz 1980). The progression of symptoms with increasing fish size, however, has not been completely investigated. In my study emphysema occurrence on certain regions of the body varied with fish size (Figures 16 and 17). Oral emphysema (buccal cavity, mandibles, and maxillaries) the most common external symptom in small trout, occurred less frequently as fish grew. Exopthalmia was uncommon except in brown trout of test 1 (35 mm and 0.4 g). Emphysema in the lateral line was also rare except in rainbow trout in test 3 (91 mm and 8.9 g). Emphysema on the fins became more prominent as fish size increased, especially for rainbow trout in tests 3 and 4. As the size of the brown trout increased, more died without external symptoms (Figure 16). Rainbow trout did not follow this trend (Figure 17).

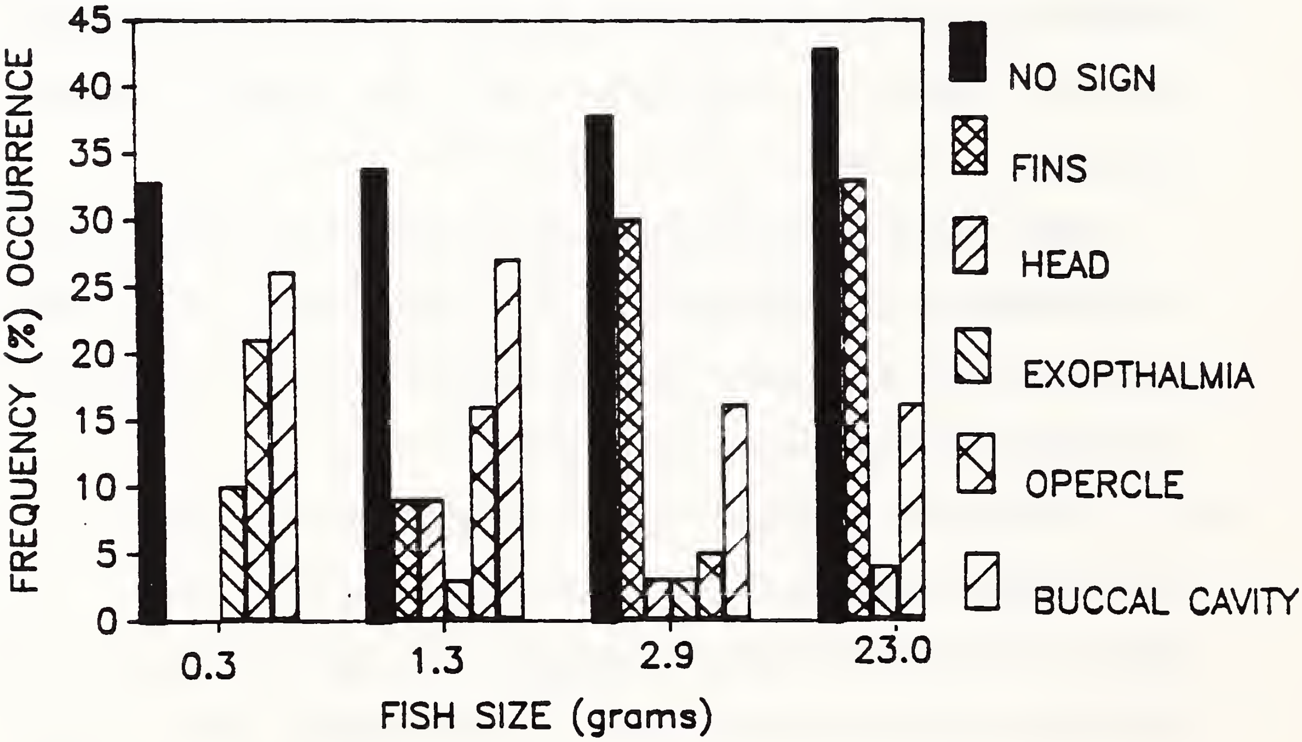

Figure 16. Frequency (%) of dead juvenile brown trout with external signs of GBT resulting from exposure to 125 % gas supersaturated water.

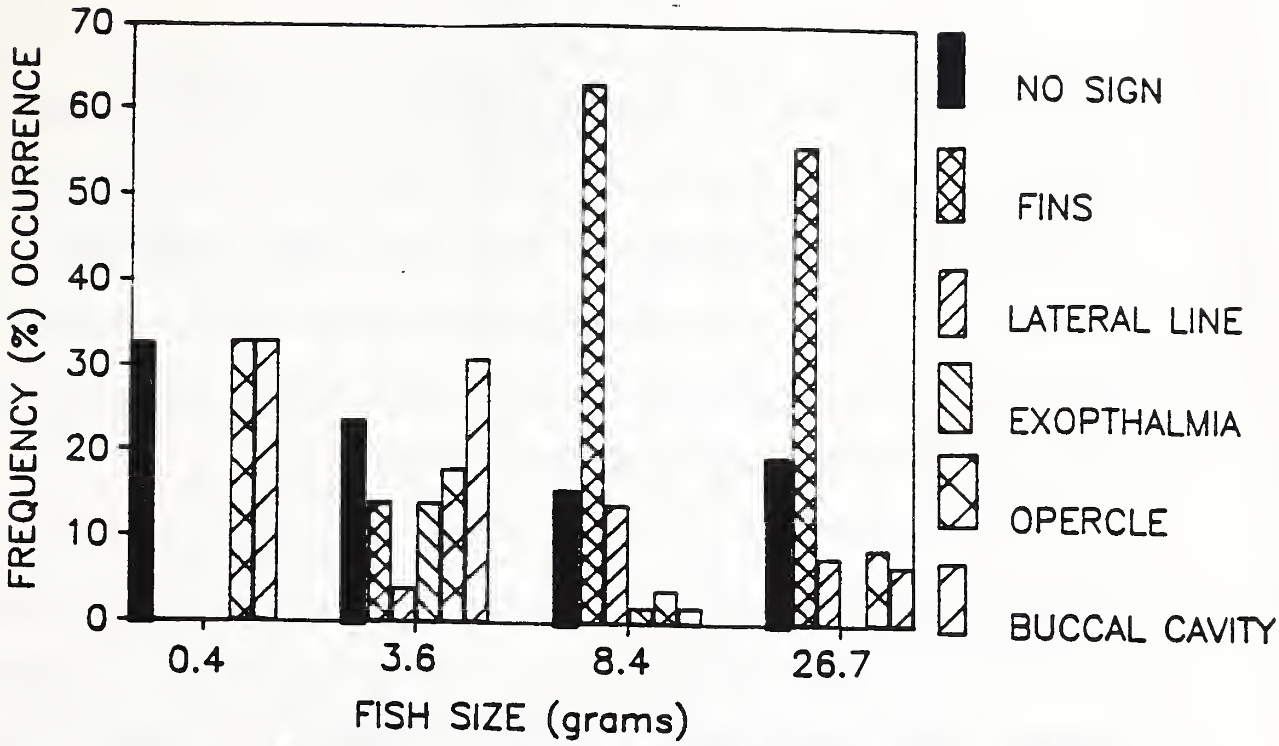

Figure 17. **Frequency (%) of dead juvenile rainbow trout with external signs of GBT resulting from exposure to 125 % gas supersaturated water.**

The higher frequency of emphysema in and around the buccal cavity of smaller brown (0.3 and 1.3 g) and rainbow trout (0.4 and 3.6 g) (Figures 16 and 17) may have been related to duration of exposure to gas supersaturated water. Dawley et al. (1975) suggested that emphysema in these areas requires more time to develop than other symptoms. In my study smaller fish survived longer than larger fish, therefore they were exposed longer. Exopthalmia was also more frequent in the smallest brown trout, which survived the longest.

Bubble formation in the lateral line is reported to be the earliest external symptom of GBT in juvenile salmonids (Schiewe and Weber 1975). Results of my study do not concur with this finding. However, I may have missed bubbles since I used only a disecting scope to examine fish during early tests and lateral line bubbles are small and may require a microscope to detect. Also, bubbles in the lateral line may have disappeared before daily removal and examination of dead fish, since they do not persist long after death (Weitkamp and Katz 1980).

The percentage of brown trout that died without external symptoms increased from 33 - 43% in tests using 0.3 to 8.3 g fish (Figure 16). This may have been due to larger brown trout dying before external symptoms formed.

Conversely, 58 - 62% of dead rainbow trout (8.9 and 26.3 g) exhibited emphysema on the fins (Figure 17). Weitkamp (1976) reported similar results for 97-112 mm juvenile chinook salmon indicating that the body region of emphysema occurrence may vary with species.

Species Influence on Susceptibility to Gas Supersaturation

Rate of brown trout mortality exposed to high gas levels (125%) was significantly greater than that of rainbow trout of similar size (Table 11). The difference in susceptibility was greatest when fish were smallest (Figure 18) and became progressively less evident as fish grew (Figures 19, 20,and 21).

Table 11. Breslow rank analysis comparing the rate of mortality for juvenile brown and rainbow trout of similar size in the high gas treatment.

Mortality comparison outcome	p-value
BT1 > RBT1	< 0.0001*
BT3 > RBT2	< 0.0001*
BT4 > RBT3	< 0.0001*
BT6 > RBT6	< 0.0002*

* Statistically different at alpha = 0.05

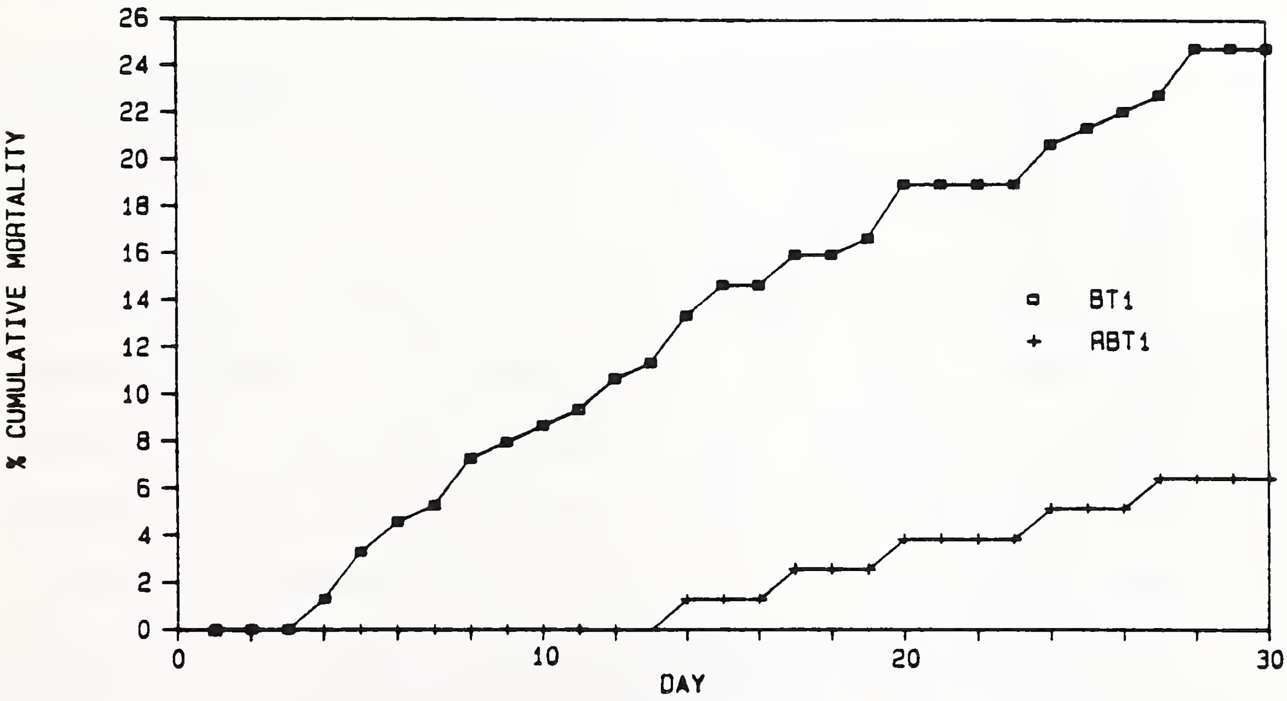

Figure 18. High treatment juvenile brown (mean beginning length and weight = 35 mm and 0.4 g) and rainbow trout (mean beginning length and weight = 34 mm and 0.4 g) percent cumulative mortality by day during test 1.

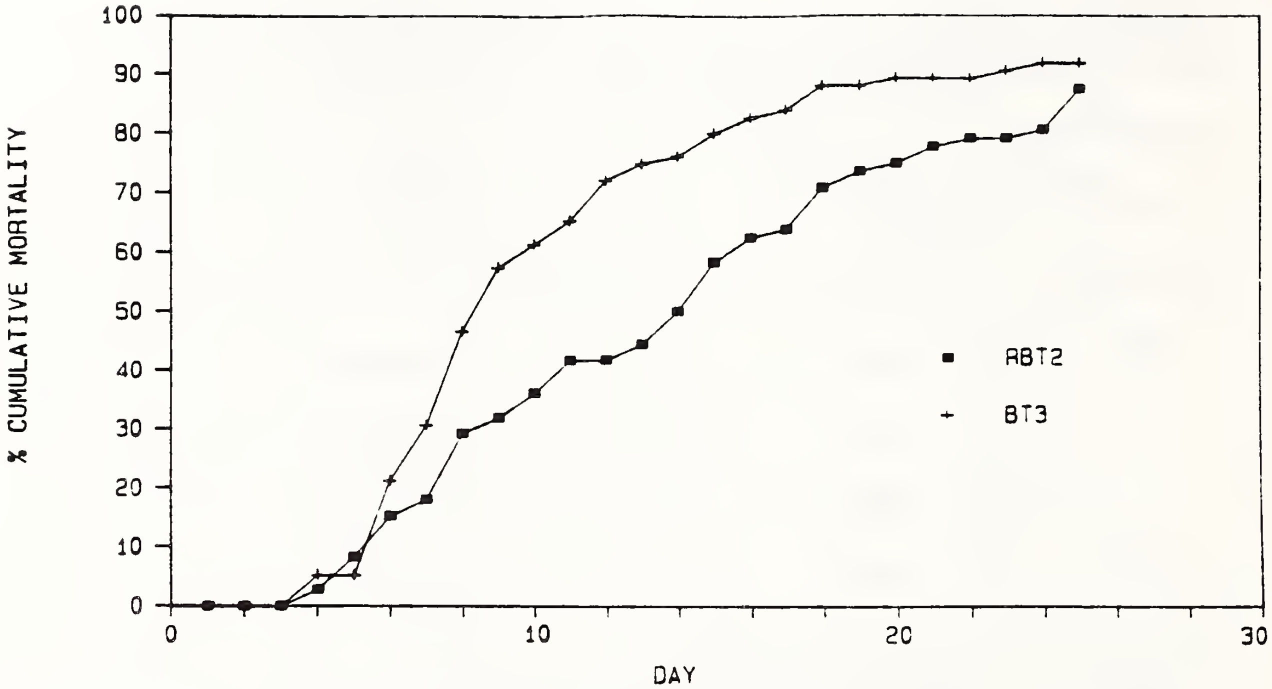

Figure 19. High treatment juvenile brown (mean beginning length and weight = 62 mm and 2.9 g) and rainbow trout (mean beginning length and weight = 71 mm and 3.4 g) percent cumulative mortality by day during tests 3 and 2, respectively.

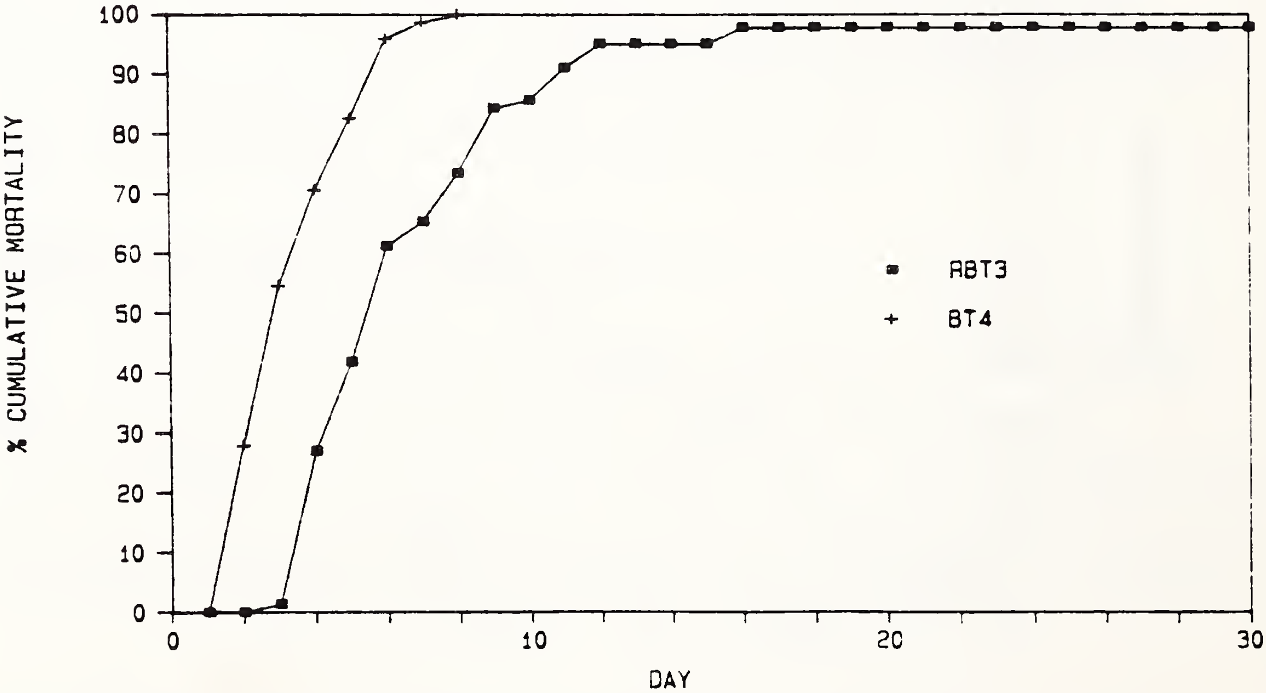

Figure 20. High treatment juvenile brown (mean beginning length and weight = 91 mm and 8.3 g) and rainbow trout (mean beginning length and weight = 90 mm and 8.9 g) percent cumulative mortality by day during tests 4 and 3, respectively.

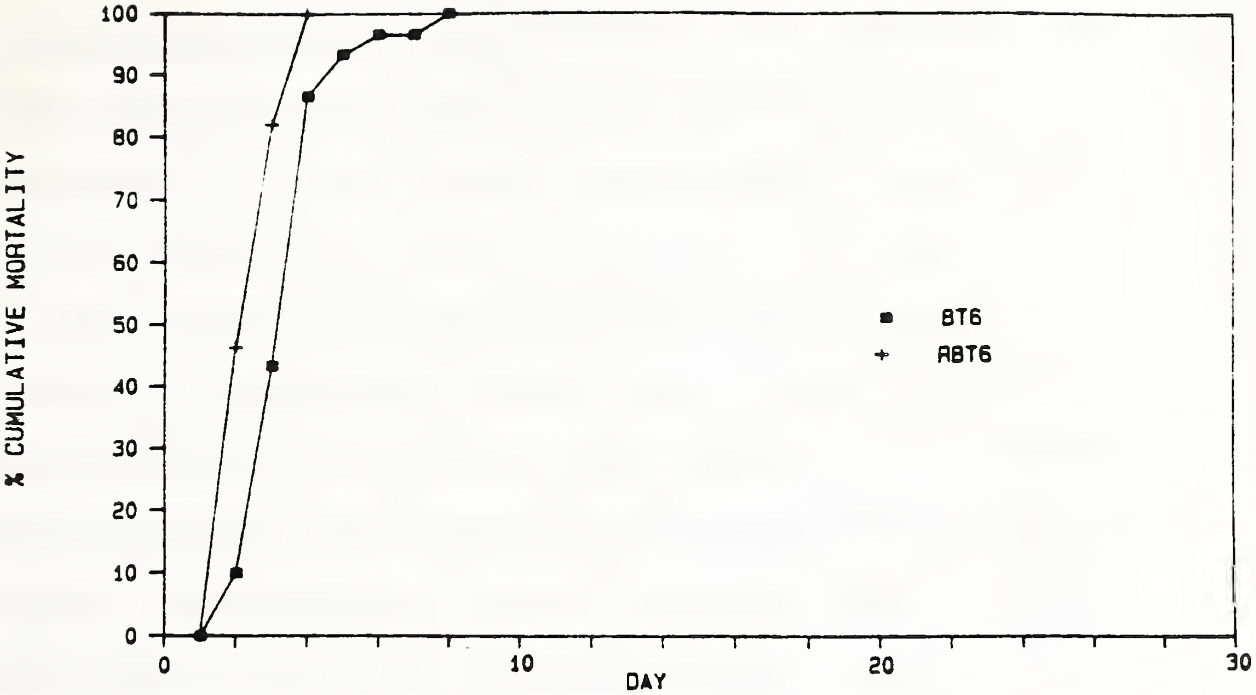

Figure 21. High treatment juvenile brown (mean beginning length and weight = 173 mm and 61.5 g) and rainbow trout (mean beginning length and weight = 179 mm and 60.5 g) percent cumulative mortality by day during test 6.

Variations in susceptibility to GBT have been reported for different species of fish. Coho salmon (O. kisutch) were more tolerant to water supersaturated with nitrogen in the presence of decreasing water temperatures than were chinook salmon or steelhead trout (Ebel et al. 1971). Coho salmon were also more tolerant (LC_{50} = 116.2%) of gas supersaturated water than were steelhead trout (LC_{50} = 114.0%) or sockeye salmon (LC_{50} = 113.9%), (Nebeker and Brett 1976). Fickeisen and Montgomery (1978) found the median time to death caused by exposure to gas supersaturated water to be longest for whitefish (Prosopium williamsoni), followed in descending order by cutthroat trout (Salmo clarki), large scaled sucker (Catostomous macrocheilus), and torrent sculpin (Cottus rhotheus). Thorn et al. (1978) exposed rainbow and brown trout to 122%, 127%, and 129% gas supersaturated water for 7-h. They reported higher brown trout mortality in the 122% exposure test, while rainbow trout mortality was larger at the two higher gas levels tested. Mean time to 50% mortality at four lethal concentrations of gas supersaturated water was longer for speckled dace (Rhinicthys osculus) than cutthroat trout (Nebeker et al. 1980). Sea bass (Dicentrarchu labrax) and striped mullet (Mugil cephalus) had similar mortality responses when exposed to 127.4% and 129.6% gas supersaturated water (Gray et al. 1985).

Differences in the anatomy of rainbow and brown trout may help provide an explanation for interspecific variation in mortality. According to to Fidler (1985) emboli form faster in a fish with more rough areas in the walls of the vascular system. Perhaps, during the earliest life stages tested, brown trout vascular tissue was more irregular than that of rainbow trout. Irregularities in vascular tissue of rainbow trout may increase with fish size explaining the similarity in mortality of the species in later tests. Thorn (1978) suggested that differences in interspecific mortality may be related to the capacity of the gas bladder. Increased capillary area on the bladder would facilitate passage of gas from the blood stream to the gas bladder, where it could be passed from the pneumatic duct. The vascular structure or functioning of the pneumatic duct may differ between brown and rainbow trout. A conclusive explanation for differences in interspecific mortality remains unknown.

Variation in occurrence of external symptoms (including exopthalmia) of GBT was noted between surviving brown and rainbow trout. Juvenile brown trout surviving exposure to 112% supersaturation exhibited more external symptoms than juvenile rainbow trout of similar size (Table 12).

Table 12. Frequency of occurrence of external symptoms of GBT on juvenile rainbow and brown trout survivors from the medium treatments (112% saturation) of tests 3, 4, 5, and 6 with associated p-values generated using Fisher's exact test.

Comparison	Fish size (mm) Rainbow	Fish size (mm) Brown	Rainbow trout survivors with signs of GBT #	Rainbow trout survivors with signs of GBT %	Brown trout survivors with signs of GBT #	Brown trout survivors with signs of GBT %	p-value
RBT3 vs BT4	100	94	4	6	12	23	0.003*
RBT4 vs BT5	138	136	6	15	32	71	0.000*
RBT6 vs BT6	182	177	4	13	14	47	0.006*

* Statistically different at alpha = 0.01

External symptoms of GBT form more readily on some species of fish than others. Ebel (1969) noted symptoms of GBT in 10 of 1,000 sockeye salmon (Oncorhynchus nerka) while no symptoms were observed in 1,762 Chinook salmon and steelhead trout (Salmo gairdneri) collected from the Columbia River. Ebel concluded that juvenile chinook salmon and steelhead trout were either using depth to compensate for the 126% saturation or were less susceptible than sockeye salmon. Exopthalmia was more common in brown than in rainbow trout reared 36 weeks in identical supersaturations (Poston et al. 1973). Observations collected between 1968 and 1973 from the Columbia River revealed that 47% of adult sockeye salmon, 40% of steelhead trout, and 26% of American shad (Alosa sapidissima) possessed external symptoms of GBT; lampreys (Ichthyomyzon sp.) showed no symptoms (Bouck et al. 1976). Thorn et al. (1978) investigated the occurrence of eye damage found in rainbow, brook, and lake trout (Salvelinus namycush). Based on data from similar exposure periods and saturation levels these researchers showed that lake trout had the highest incidence of eye damage followed by rainbow, brook, then brown trout. Seventy-two percent of smallmouth bass (Micropterus dolomieui) and 84% of northern squawfish (Ptychocheilus oregonensis) collected simultaneously by anglers in the lower Snake and Columbia River drainages had external lesions associated with GBT (Montgomery and Becker 1980).

The difference in external symptom formation found between species in my tests appears, to be related their physiology since fish were kept in identical environments.

Emphysema formation may be the result of excessive transport of gas from water into the epidermal cells of fish. The The rate and amount of gas that passes through the skin is inversely proportional to epidermal thickness and directly proportional to capillary density beneath the epidermis (Hoar and Randall 1970). Brown trout may have either thinner skin or greater vascularization beneath the the skin than rainbow trout.

Recovery from a Single Exposure to Gas Supersaturation

Juvenile brown and rainbow trout recovery (loss of external symptoms) from GBT varied with severity of external symptoms. Less severely affected rainbow trout recovered more often and faster (Table 13 and Figure 22). Five of six rainbow trout that did not recover within 30-d exhibited eye damage characterized by severe unilateral and bilateral exopthalmia, hemorrhaging, cloudiness, corneal cataracts, or bubbles in the eye orbit.

Juvenile brown trout with emphysema and mild exopthalmia recovered within 30-d. However brown trout with widespread emphysema and severe exopthalmia (GBT rating 3, Table 6) recovered less often (Table 14).

Table 13. Recovery of juvenile rainbow trout (228 ± 17 mm and 124.6 ± 30.7 g) exposed to 117% gas supersaturated water for 9-d February 1 - 9, 1987.

GBT[a] rating	Beginning number	Number dead by day 30	Number with symptoms remaining after 30-d
1	5	0	0
2	7	0	1
3	8	1	5

a = see Table 6

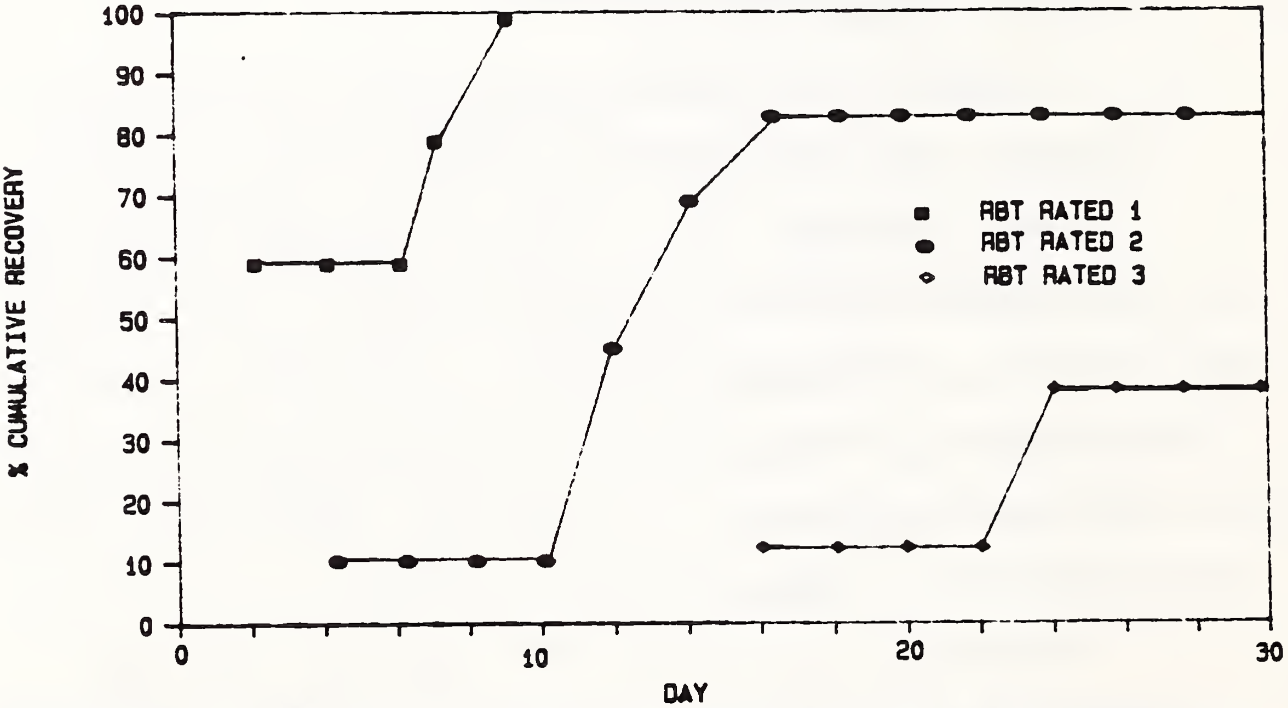

Figure 22. Comparison of GBT severity and recovery rate of juvenile rainbow trout (228 ± 17 mm and 125 ± 31 g) by 2-d intervals February 9 - March 12, 1987 (See Table 6 for severity definitions).

Exopthalmia developed during recovery in the two fish that did not recover from 17-d exposure to 111% gas supersaturated water (Table 14). Two brown trout rated 3 after exposure to 117% TGP for 5-d died rapidly after transfer to a recovery tank.

Table 14. Recovery of juvenile brown trout (133 ± 21 mm and 27.5 ± 9.5 g) by severity level, following exposure to various levels and durations of exposure to gas supersaturation, February 9, 1987.

GBT[a] rating	Beginning number	Exposure duration (days)	Gas level (%TGP)	Number dead after 30-d	Number with symptoms remaining after 30-d
1	15	17	111	0	0
1	10	30	111	0	0
2	3	5	117	0	0
2	2	30	111	0	0
3	2	5	117	2	0
3	3	17	111	0	2

a = see Table 6 for rating description

Recovery from GBT has been documented for several species. Emphysema and exopthalmia regressed in scup (Stenotomus chrysops) within 24-h of removal from shallow tanks to tanks with pressure equal to 16 feet of water (Gorham 1901). Cutthroat, rainbow, and steelhead trout fingerlings raised in hatchery troughs at Puyallup Hatchery of the Washington State Department of Game showed high incidence of GBT symptoms. Transfer of fingerlings to an outside pond eliminated all external symptoms (Rucker and Hodgeboom 1953). Impaired swimming ability of juvenile chinook salmon exposed to 120% supersaturation was rectified within 2-h after removal to 100% saturated water (Schiewe

1974). Eratic swimming and yolk sac emboli were alleviated in coho salmon sac fry using a recompression chamber (Adams 1974). Dawley et al. (1976) determined that 2 weeks was an adequate recovery period for juvenile chinook with GBT acquired from exposure to 110 - 120% supersaturation for 120-d. Ninety-one to 95% percent of juvenile chinook salmon surviving 10 - 20-d exposure in 1 - 4 m of water of 120 - 131% gas supersaturation lost all external symptoms of GBT after 20-d in an unsupersaturated environment (Weitkamp 1976). Apparently most fish with GBT will recover if moved to an unsaturated environment.

Eye damage in surviving salmonids may be the principal permanent effect of exposure to sublethal doses of gas supersaturated water. Dawley et al. (1976) removed chinook salmon with GBT to a non-supersaturated environment in which 95% of the fish recovered. The remaining 5% suffered hemorrhaging or bubbles in the orbit of the eye. The degree to which this condition could affect the well-being of the fish depends on the severity of the eye damage.

Physical degradation of the eye components from exopthalmia can be irreversible. Corneal lesion formation can be a precursor to loss of eye function (Hoffert and Fromm 1965). Machado et al. (1987) reported that juvenile rainbow trout exposed to 116.9 ± 0.7 percent nitrogen and 110.1 ± 4.6 percent oxygen supersaturation experienced with eye damage characterized by formation of space between the capillary layer of the choroid and the pigment epithelial layer of the retina, and degenerative vacuolization of the optic nerve, musculature, adjacent connective tissue, and glandular tissues of the fish.

Two brown trout and one rainbow trout that eventually died were removed from gas supersaturated water during the "convulsive stage". This stage usually preceded death by a few minutes and is characterized by side-swimming, abnormal buoyancy, whirling movements accompanied by inactivity, and spasmodic convulsions (Machado et al. 1987). At this point emboli formation in the vascular system was probably at an irreversible stage.

The occasional formation of exopthalmia during recovery was perplexing. I originally attributed this to frequent handling of fish for rating, sharp blows against recovery tank walls, and exposure to the low level of supersaturation in the recovery tanks. However, post-exposure eye damage has been documented and interpreted differently. Bouck et al. (1976) reported perforation of the cornea, lens loss, and acute necrosis of the eyeball in adult sockeye salmon after removal from the supersaturated water of the Columbia River. The capture process and holding environment were dismissed as primary factors responsible for post-capture eye damage. The researchers hypothesized that the main cause of this problem was previous exposure to gas supersaturated water, a theory he supported with data from other work completed on the Columbia River. A definitive explanation for post-exposure eye damage is still unavailable.

Effects of Repeated Exposure

Recovery From Repeated Exposure:

The recovery (loss of external symptoms) of juvenile brown trout from three 30-d exposures to 118% gas supersaturated water was influenced by severity of external symptoms. Most fish rated 1 (Table 6) after exposure recovered (Table 15). Two of 12 fish rated 1 after the first exposure did not totally recover due to eye damage incurred during the recovery period. Fifty percent of fish rated 2 after the first two exposures recovered. Fish that did not totally recover had permanent eye damage. Both fish rated 3 after initial exposure died during recovery (Table 15). One of these fish was in the "convulsive stage" when it was removed from gas supersaturated water. The second fish suffered from bilateral exopthalmia, impaired swimming, and severe emphysema. Permanent eye damage prohibited recovery of fish rated 3 after the second exposure. One of two fish that had no external symptoms after the second exposure was was killed accidently when the recovery tank was cleaned. The third 30-d recovery period was affected when water temperature increased to 23 °C for 24-h. Three of the six survivors died from a Pseudomonad sp. infection.

One of the three surviving fish was rated 1 and totally recovered within 30-d, while one rated 2 and one rated 3 did not recover because of permanent eye damage (Table 15).

Table 15. GBT rating,mortality and percent recovery of juvenile brown trout (fish size on day 1 of testing = 164 ± 17 mm and 43.2 ± 14.4 g) by GBT rating exposed to 118% gas supersaturated water for 120-h, three times and given 30-d to recover between exposures June 6 - September 18, 1987.

Rating	First exposure			Second exposure			Third exposure		
	# of fish	# dead by day 30	% re-covery by day 30	# of fish	# dead by day 30	% re-covery by day 30	# of fish	# dead by day 30	% re-covery by day 30
0	0	0	---	2	1*	---	0	0	0
1	12	0	83	0	0	---	2	1*	100
2	6	0	50	4	0	50	3	2*	0
3	2	2	0	1	0	0	1	0	0

*Death not related to GBT

Overall, recovery of juvenile brown trout from GBT decreased with each exposure (Figure 23). Extreme eye damage and progression to the convulsive stage were primary reasons for lack of recovery.

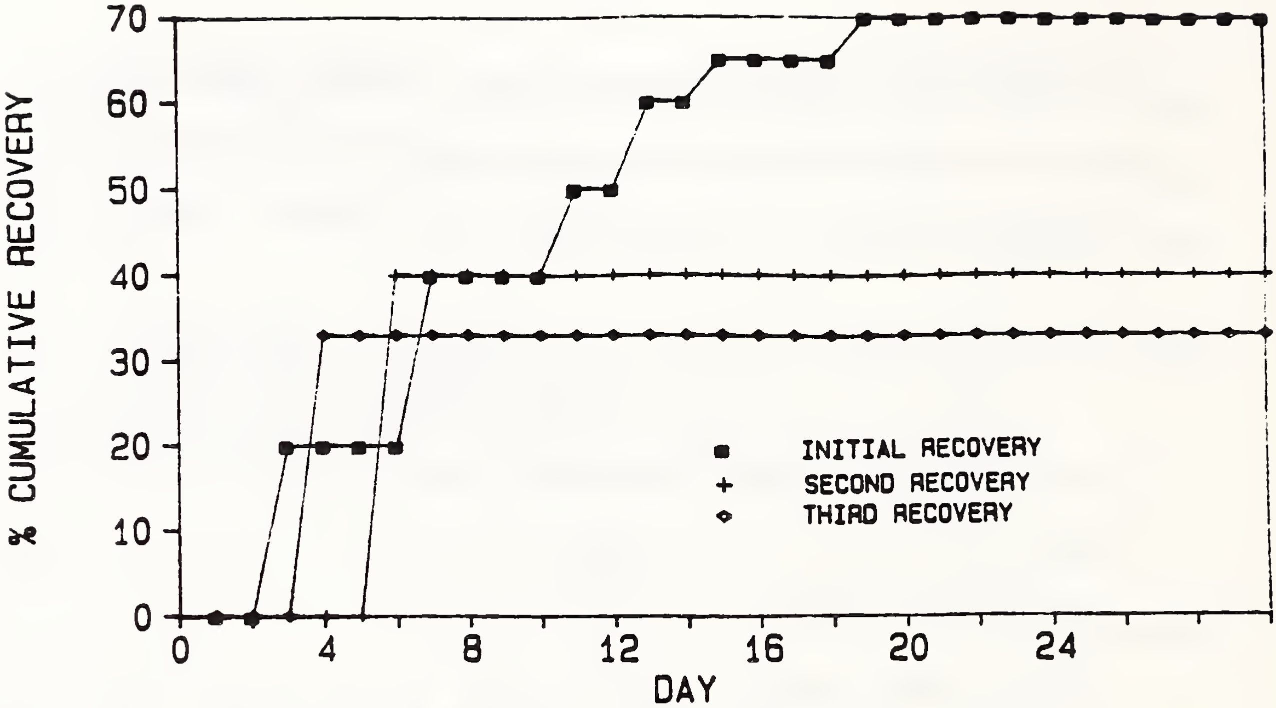

Figure 23. Percent cumulative recovery for juvenile brown trout (fish size on day 1 of testing = 164 ± 17 mm and 43.2 ± 14.4 g) from GBT calcualted by combining GBT rating groups 1, 2, and 3 (see Table 6) from three 120-h exposure tests conducted June 6 - September 18, 1987.

Previous eye damage often recurred after successive exposures. Eye damage of this nature was thoroughly discussed under single exposure testing.

Symptom Severity Associated with Repeated Exposure:

Symptom severity did not follow a predictable pattern for fish exposed 5-d to 118% gas supersaturation. Severity of external symptoms in the second exposure increased in sone fish, decreased in others, and sometimes was unchanged (Table 16).

Table 16. Changes in symptom severity of juvenile brown trout (fish size on day 1 of testing = 164 ± 17 mm and 43.2 ± 14.4 g) exposed three times for 120-h to 118% gas supersaturated water with 30-d intervals between exposures; June 6 - September 18, 1987.

Time interval	Proportion of fish with more severe symptoms	Proportion of fish with less severe symptoms	Proportion of fish with similar symptoms	Proportion of fish that died during exposure
Exposure 1 - 2	3/14	2/14	2/14	7/14
Exposure 2 - 3	2/6	2/6	2/6	0/6

Fifty eight percent of surviving fish developed new symptoms and 42% exhibited recurring symptoms. Of those with recurring symptoms 15% were of increased severity.

Increased symptom severity in fish surviving an initial exposure to gas supersaturated water was noted by Gorham (1901). He subjected scup to a sequence of decompression/ recompression/ decompression three to four times for 30-min intervals. Bubbles that formed in the eye during initial decompression increased in size until the eyes protruded in later decompression. Some juvenile brown trout may have become sensitized to GBT. Sensitizing may consist of enhancement of emboli producing nucleation sites or damage to the capillary beds causing a loss of ability to transfer gases.

Acclimization and Tolerance to Repeated Expsoure:

Different proportions of GBT rating were observed in the three progressive exposures. Mortality (rating 4;Table 6) of juvenile brown trout was significantly greater during the first and second exposure to gas supersaturated water than during the third exposure (Tables 17 and 18). A significantly greater proportion of fish were rated 1 after the first exposure than in subsequent exposures (Tables 17 and 18). The proportion of fish rated 2 increased significantly from exposure 1 to exposure 3 (Tables 17 and 18). The proportion of fish rated 3 increased with each exposure, however the change was not significant (Tables 17 and 18).

Table 17. Gas bubble trauma rating for juvenile brown trout (fish size on day 1 of testing = 164 ± 17 mm and 43.2 ± 14.4 g) by number and percent composition after exposure to 118% gas supersaturated water for 120-h three times at 30-d intervals from June 6 - September 18, 1987.

GBT[a] rating	First exposure #	First exposure %	Second exposure #	Second exposure %	Third exposure #	Third exposure %
0	0	0	2	12	0	0
1	12	24	0	0	2	33
2	6	12	4	23	3	50
3	2	4	1	6	1	17
4	30	60	10	59	0	0

a = see Table 6 for rating description

Table 18. Comparison of GBT severity in juvenile brown trout (fish size on day 1 of testing = 164 ± 17 mm and 43.2 ± 14.4 g) exposed to 118% gas supersaturated water three times at 30-d intervals June 6 - September 18, 1987 using Fisher's Exact Test.

Comparison GBT rating[a]	p - value
Exposure 1 Vs Exposure 2	
0 = 0	0.067
1 > 1	0.017*
2 = 2	0.921
3 = 3	0.831
4 = 4	0.581
Exposure 2 Vs Exposure 3	
0 = 0	0.554
1 = 1	0.059
2 = 2	0.239
3 = 3	0.941
4 > 4	0.013*
Exposure 3 Vs Exposure 1	
0 = 0	0.067
1 = 1	0.842
2 > 2	0.046*
3 = 3	0.972
4 < 4	0.007*

*Statistically significant at alpha = 0.05
a = see Table 6 for rating description

Repeated exposure to gas supersaturated water may reveal juvenile salmonids are able to acclimate to gas supersaturation. Meekin and Turner (1974) attempted to acclimate juvenile summer chinook salmon to nitrogen supersaturation by conditioning them in progressively higher levels of water supersaturated with nitrogen for varying periods of time. Severe mortality occurred when nitrogen saturation was increased to 135%, regardless of conditioning; chinook salmon survived exposure to 135% TGP longer when removed to water of 100% saturation for 8-h/d than if exposed continuously. Weitkamp (1976) exposed juvenile chinook to 125% TGP for a sequence of three exposure/non-exposure periods. When the sequence was 16-h exposure and 8-h recovery, juvenile chinook developed external signs of GBT and were twice as likely to die as fish exposed for 8-h given 16-h to recover. Chinook salmon, coho salmon, steelhead trout, rainbow trout, mountain whitefish, and large mouth bass (_Macropterus salmoides_) exposed to 110 - 130% nitrogen for 8-h given 16-h to recover lived longer than fish exposed constantly to similar nitrogen supersaturations (Blahm et al. 1976). Although these investigations show that relief form saturated conditions can extend the survival time of most fish, they do not document acclimation.

Juvenile brown trout in my study did not appear to acclimate to gas supersaturated water. External symptom severity did not decrease with repeated exposure (Table 18). However some brown trout were more tolerant of high dissolved gas levels. None of the six fish remaining after two exposures died when exposed a third time.

Tolerance to gas supersaturation was demonstrated by Thorn et al. (1978) who exposed bluegill sunfish to supersaturations ranging from 113 - 124%. Survivors of these tests were subjected to 124% then 127% gas supersaturated water, but showed no external GBT symptoms or mortality.

Tolerance is described in the literature as a heritable trait. Gray et al. (1982) showed that carp (*Cyprinus carpio*) and black bullhead (*Ictulurus melas*) of the Columbia River were more tolerant of gas supersaturation than those from Italy. The researchers suggested that this difference may be due to genetic adaptation traceable to historical supersaturation of Columbia River water. Cramer and McIntyre (1975) hypothesized that a selection for fall chinook salmon with the phenotypes that promoted greatest resistance to GBT occurred in the Columbia River. A similar selection may be occurring in the Bighorn River below Yellowtail Afterbay Dam.

Sublethal Effects of Exposure to Gas Supersaturated Water

Growth:

Exposure of juvenile brown and rainbow trout to 112% gas supersaturated water (medium treatment) did not affect growth. Beginning and final mean weights of medium treatment fish from tests 1, 3, 5, and 6 were not significantly different from control fish (Table 19).

Growth data from medium treatment tests 2 and 4 were not used because mortality, which may have been related to fish size, occurred and could have biased results.

Table 19. Effect of gas supersaturated water on the growth of control (104%) and medium treatment (112%) brown and rainbow trout from tests 1, 3, 5, and 6 and the associated p-values calculated using the Man-Whitney nonparametric rank test (alpha = 0.05).

Species	Beginning mean weight (g/fish)			p-value	Final mean weight (g/fish)			p-value
	control		medium treatment		control		medium treatment	
Brown	21.5	=	21.9	0.795	20.5	=	20.0	0.863
Rainbow	37.5	=	40.0	0.817	39.9	=	39.9	0.977

Some workers have shown that exposure to gas supersaturated water affects growth of surviving fish. Brown and rainbow trout reared in 120% gas supersaturated water grew more slowly than those reared in 108% gas supersaturated water for 36 weeks (Poston et al. 1973). Northern squawfish exposed to 120% gas supersaturated water for 12-d consumed an average of 12 g/d less food than did squawfish exposed to 100% saturation (Bentley et al. 1976). Yearling lake trout growth and food conversion was reduced during exposure to sublethal levels of gas supersaturation (Thorn et al. 1978). Stress experienced by fish during exposure to gas supersaturated water may be tied to decreased fish growth. Stress induced by unfavorable environmental conditions affects fish production traits (Piper et al. 1982). Exposure to sublethal levels of supersaturated water may cause improper functioning of the gastrointestinal tract. Stroud and Nebeker (1976) found that food was held in the stomach of juvenile steelhead trout up to 54-h at 120% TGP and 93-h at 115% TGP. They determined that this time period was longer than would be expected, possibly because of decreased peristalic movement of the gut. Poorer growth of fishes exposed to gas supersaturated water in these investigations may be due to inefficient food digestion attributable to gas supersaturated water.

Other researchers found that gas supersaturation does not affect fish growth. Juvenile steelhead trout surviving 40-d exposure to gas supersaturated water with delta-P from 150 - 180 mm showed no significant decrease in growth (Nebeker et al. 1978). Channel catfish (Ictalurus punctatus) surviving exposure to 104.7 - 115% TGP for 35-d showed no reduced growth or signs of GBT, yet some died (Colt et al. 1985). The response appeared to be all or nothing; fish either died or showed no growth effects.

During my tests, 112% TGP did not impair feeding behavior, physiological growth factors, or cause significant mortality in juvenile brown or rainbow trout within the length and weight range I tested. However, some mortality occurred in 30-d bioassays when percent TGP surpassed 112%. The "all or nothing response" identified by Colt et al. (1985) seems applicalble to my study.

Predation Tests in Tanks:

Tests run in circular tanks using the procedure of Bams (1967) showed no difference in predation vulnerability between juvenile brown and rainbow trout exposed to gas supersaturated water and non-exposed fish (Tables 20, 21, 22, 23 and 24). Problems with the large size of rainbow trout prey used during the 112%/30-d tests made it difficult for predators to consume a suitable number of prey before prey recovery from GBT (Table 20). Predator density was increased during the remaining tests (Tables 21, 22, 23, and 24) to avoid this problem.

Reduced fitness of prey can increase their vulnerability to predation . Kania and O'Hara (1974) found that the ability of misquito fish (Gambusia affinia) to avoid predation by largemouth bass was impaired after exposure to sublethal concentrations of mercury. Rainbow trout, chinook salmon, and sockeye salmon experienced elevated predation vulnerability after exposure to high water temperature (Coutant 1973, Sylvester 1972).

Table 20. Number of survivors (beginning number = 25), ratios of instantaneous predation rates (dp), and chi-square statistic corrected for continuity (X^2c) for predation tests with juvenile rainbow trout prey (77 ± 5 mm) after exposure for 30-d to 112% gas supersaturated water.

Test	Number surviving		Chi-square (1 df)	dp
	Treatment (expected)	Control (expected)		
1	21 (17.5)	14 (17.5)	1.4	0.301
2	14 (14)	14 (14)	0.0	1.000
Total of chi-squares(2df)			1.4	
Chi-square of totals (i.e, pooled chi-square 1 df)	35 (31.5)	28 (31.5)	0.777	
Heterogeneity chi-square (1df)			0.623 $0.75 > p > 0.50$	
Chi-square correction for continuity			$X^2c = \frac{([35-28]-1)^2}{73} = 0.493$ $0.50 > p > 0.25$	

Table 21. Number of survivors (beginning number = 25), ratios of instantaneous predation rates (dp), and chi-square statistic corrected for continuity (X^2c) for predation tests with juvenile rainbow trout prey (45 mm) after exposure for 30-d to 124% gas supersaturated water.

Test	Number surviving		Chi-square (1 df)	dp
	Treatment (expected)	Control (expected)		
1	10 (13.5)	17 (13.5)	1.815	2.376
2	16 (14.5)	13 (14.5)	0.301	0.682
3	12	5	2.882	0.456
Total of chi-squares(2df)			5.007	
Chi-square of totals (i.e, pooled chi-square 1 df)	38 (31.5)	35 (31.5)	0.123	
Heterogeneity chi-square (1df)			4.884 $0.10 > p > 0.05$	

Chi-square correction for continuity $X^2c = \frac{([38-35]-1)^2}{63} = 0.0541$

$0.90 > p > 0.75$

Table 22. Number of survivors (beginning number = 25), ratios of instantaneous predation rates (dp), and chi-square statistic corrected for continuity (X^2c) for predation tests with juvenile brown trout prey (69 ± 7 mm) after exposure for 30-d to 110% gas supersaturated water.

Test	Number surviving		Chi-square (1 df)	dp
	Treatment (expected)	Control (expected)		
1	15 (17)	23 (17)	1.684	6.126
2	10 (14.5)	18 (14.5)	2.285	2.789
Total of chi-squares(2df)			3.969	
Chi-square of totals (i.e. pooled chi-square 1 df)	25 (34.5)	41 (34.5)	2.249	
Heterogeneity chi-square (1df)			1.520 0.25 > p > 0.10	
Chi-square correction for continuity	$X^2c = \frac{([25-41]-1)^2}{69}$		= 3.260 0.10 > p > 0.05	

Table 23. Number of survivors (beginning number = 25), ratios of instantaneous predation rates (dp), and chi-square statistic corrected for continuity (X^2c) for predation tests with juvenile brown trout prey (56 ± 7 mm) after exposure for 30-d to 112% gas supersaturated water.

Test	Number surviving		Chi-square (1 df)	dp
	Treatment (expected)	Control (expected)		
1	14 (14)	24 (14)	0.000	1.000
2	10 (11)	12 (11)	0.182	1.249
Total of chi-squares(2df)			0.182	
Chi-square of totals (i.e, pooled chi-square 1 df)	24 (25)	26 (25)	0.080	
Heterogeneity chi-square (1df)			0.102 p = 0.75	

Chi-square correction for continuity $X^2c = \frac{([26-24]-1)^2}{50} = 0.020$

$0.90 > p > 0.75$

Table 24. Number of survivors (beginning number = 25), ratios of instantaneous predation rates (dp), and chi-square statistic corrected for continuity (X^2c) for predation tests with juvenile brown trout prey (56 ± 5 mm) after exposure for 13-h to 130% gas supersaturated water.

Test	Number surviving		Chi-square (1 df)	dp
	Treatment (expected)	Control (expected)		
1	12 (11.5)	11 (11.5)	0.043	0.894
2	14 (11)	8 (11)	1.636	0.509
3	13 (14)	15 (14)	0.143	1.280
4	9 (12.5)	16 (12.5)	1.960	2.289
Total of chi-squares(2df)			3.782	
Chi-square of totals (i.e, pooled chi-square 1 df)	48 (49)	50 (49)	0.041	
Heterogeneity chi-square (1df)			3.741 0.10 > p > 0.05	

Chi-square correction for continuity

$$X^2c = \frac{([48-50]-1)^2}{98} = 0.010$$

0.95 > p > 0.90

Brook trout consumed more atlantic salmon that had been exposed to insecticide than unexposed fish (Hatfield and Anderson 1972). Hertig (1967) concluded that bluegill and largemouth bass suffering from columnaris disease, parasitism, or starvation were more vulnerable to predation than healthy fish. Predators selected prey impaired because they were slow swimming and easy to catch. Hatchery reared sockeye salmon fry did not swim as well as wild fry, leading to increased vulnerability to predation (Bams 1967).

Gas Bubble Trauma affects fish swimming performance and vision. These impairments could make it easier for predators to discover and capture GBT inflicted fish. However, under laboratory conditions I did not observe increased vulnerabilty to predation.

Predation Tests in the Experimental Stream:

Predation tests in the experimental stream showed that brown trout exposed to 118% gas supersaturated water for 5-d experienced significantly increased vulnerability to predation (Table 25). There was no statistically significant selective predation on brown trout exposed for 4, 6, or 7 days (Table 25), nor on rainbow trout exposed for 11 to 12 days (Table 26).

Table 25. Ratio of instantaneous predation rates (dP) of juvenile brown trout exposed to 118% gas supersaturated water and non-exposed fish.

Duration of exposure (days)	Mean fish length (mm ± SD)	Number of replicates	Number Surviving		dp
			treatment	control	
4	46 ± 3	1	14	19	2.113
5	47 ± 4	1	13	21	3.751*
6	45 ± 3	1	13	15	1.280
7	46 ± 4	1	15	13	0.781

*Significantly different using Fisher's exact test at alpha = 0.05

Table 26. Ratio of instantaneous predation rates (dP) of juvenile rainbow trout exposed to 118% gas supersaturated water and non-exposed fish.

Duration of exposure (days)	Mean fish length (mm ± SD)	Number of replicates	Number Surviving		dp
			treatment	control	
11	58 ± 7	1	12	8	0.644
12	61 ± 5	1	7	6	0.892

*Significantly different using Fisher's exact test at alpha = 0.05

Juvenile brown trout exposed to 118% gas supersaturation for 5-d may have been most susceptible to predation because of the nature of fish response to supersaturated water. Some fish die quickly, some acquire severe symptoms of GBT and die slowly and some are never affected. I observed that the number of brown trout with external symptoms of GBT peaked on day 5 of exposure. Fish removed from the exposure system for a given test were the first to display symptoms. Hence, remaining fish after each successive test were those which werre most tolerant of supersaturation. The trend in instantaneous mortality rates supports this hypothesis (Figure 25) and may explain why predation was greatest on fish exposed to gas supersaturation for 5-d.

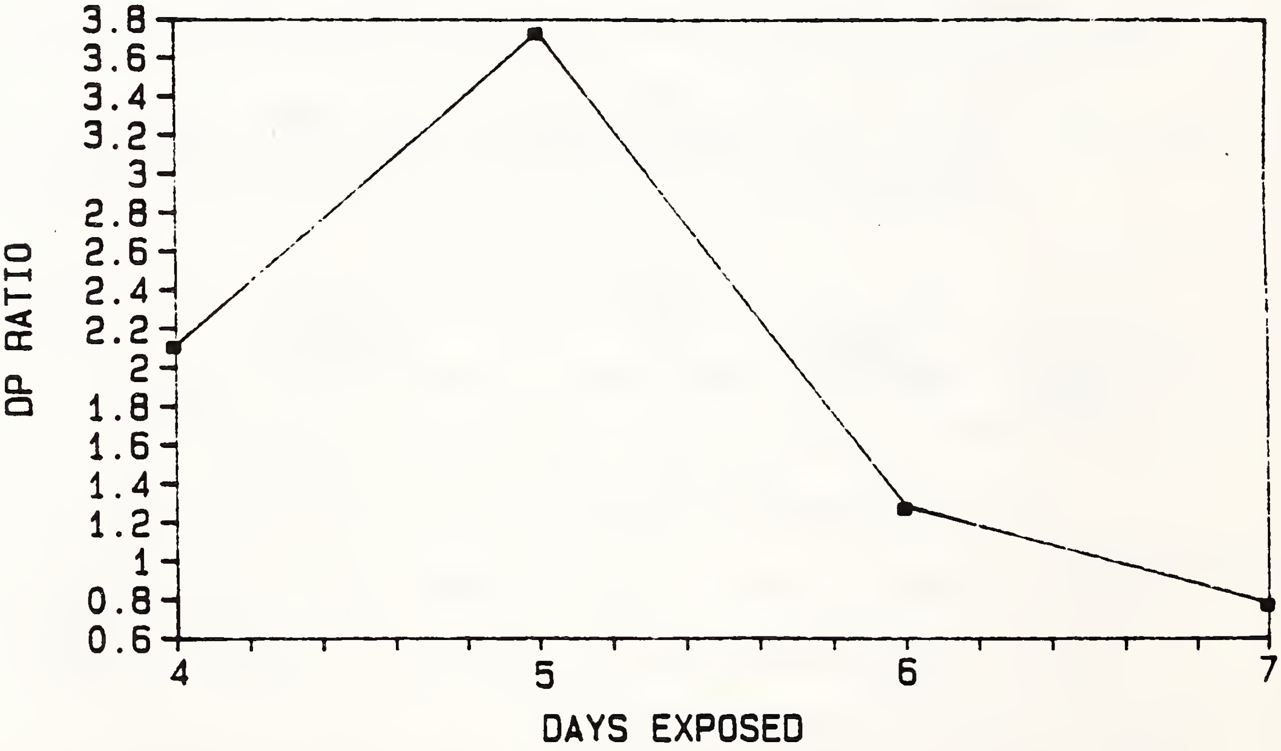

Figure 24. Ratio of instantaneous predation rates (dp) by rainbow trout predators on juvenile brown trout exposed 118% gas supersaturated water for 4 - 7-d and control fish (dp > 1 signifies greater predation on brown trout exposed to gas supersaturation).

The ability of rainbow trout to rapidly recover from overinflation of the swimbladder may decrease their susceptibility to increased predation from exposure to gas supersaturated water (Table 27). Schiewe (1974) reported that swimming impairment of juvenile chinook salmon caused by overinflation of the swimbladder was reduced within 2-h of removal from 120% gas supersaturated water to equilibrated water. During my second series of rainbow trout tests overinflation of the swimbladder was the only symptom in 18 of the 26 affected prey fish.

Tests to evaluate recovery time showed that rainbow trout released in a non-supersaturated pond lost all signs of excess buoyancy in 1 - 3 min. More than 3 min were required for the predators to discover the prey during stream predation tests. Rainbow trout prey may have expelled excess gas via the pneumatic duct, thereby regaining equilibrium prior to predator feeding.

Predators were not replaced between tests which also may have biased the study. Coutant (1973) suggested that reusing predator fish did not bias predator-prey study results. However, with time, predators may become more efficient at capturing prey. The four predators in the experimental stream were trained to feed on prey three to four times prior to testing and were used six times during testing. Werner et al. (1981) found that bluegill foraging efficiency increased four-fold over the course of six to eight foraging opportunities and Ware (1971) reported that rainbow trout increased foraging efficiency six-fold in 8-d. My rainbow trout predators may have become too efficient at consuming prey, thereby biasing results.

Disease Resistance:

Significantly more bacteria were identified in kidney samples of fish challenged with bacteria than in unchallenged fish (Table 27).

Table 27. Two sample t-test analysis of the number of *A. hydrophila* identified in kidney samples of juvenile brown trout challenged with bacteria and unchallenged fish.

Duration (min) challenged fish were treated w/bacteria	Comparison			P-value
	challenged fish (w/bacteria)		unchallenged fish (no bacteria)	
10	no GBT	>	no GBT	0.0039*
20	no GBT	>	no GBT	0.0010*
30	no GBT	>	no GBT	0.0000*
40	no GBT	>	no GBT	0.0000*
10	GBT	>	GBT	0.0003*
20	GBT	>	GBT	0.0001*
30	GBT	>	GBT	0.0000*
40	GBT	>	GBT	0.0000*

*Significantly more *A. hydrophila* in juvenile brown trout challenged with bacteria than in unchallenged fish at alpha = 0.05

Juvenile brown trout with GBT from exposure to 118% gas supersaturated water challenged with bacteria for 20 - 40 min had significantly more bacteria in kidney samples than fish similarly challenged but not exposed to gas supersaturated water (Table 28). Results of the second replicate test were discarded because control fish died from a Pseudomonas sp. infection unrelated to experimental procedure.

Table 28. Two sample t-test analysis of the number of A. hydrophila identified in kidney samples of juvenile brown trout (196 ± 13 mm and 74.5 ± 17.3g) not exposed to gas supersaturated water (control) and fish (198 ± 12 mm and 75.4 ± 16.2 g) with GBT (test) from exposure to 118% supersaturated water for 120-h.

Challenge duration (min)	Mean number of bacterium/kidney sample		p-value
	control	test	
10	48 ± 9	53 ± 3	0.4234
20	54 ± 3	65 ± 4	0.0672*
30	70 ± 3	79 ± 3	0.0145*
40	85 ± 4	92 ± 3	0.0535*

*Significantly more A. hydrophila in juvenile brown with GBT at alpha = 0.10

Bacteria of the genus Aeromonas sp. are ubiquitous microbes of water and are commonly found in the alimentary tract of healthy salmonids (Trust and Sparrow 1974). However, under conditions of stress, A. hydrophila can become an opportunistic pathogen. Thorpe and Roberts (1972) described a septicemic outbreak in spawning brown trout of Loch Leven, Scotland. Grayish skin ulcerations, abdominal distention, swelling and discoloration of internal organs, secretion of a yellow mucous in the intestine and subsequent swelling of the anal vent are common in infected fish during epizootics of motile aeromonad septicemia (Piper et al. 1986).

Trust (1986) speculated that bacterial infection may result from penetration of the thick mucosal layer of the skin. Post (1983) hypothesized that soon after a bacterium enters the tissue or blood stream of a fish, it is phagocytized and transported to the spleen or anterior kidney. Macrophages may break the bacterium into separate antigenic components. B-cells and plasma cells may produce antibodies specific to these antigens.

This information is complicated, but in general it appears that stress and increased systemic access can facilitate bacterial disease. During my tests, the stress caused by GBT may have impaired the defense (macrophages) and immune system (antibody production) functioning.
The blistering of the epidermis common to emphysema may have provided bacteria open passage to capillary beds. Severe exopthalmia characterized by freely bleeding open eye wounds also may have provided bacteria direct access to the bloodstream of the fish.

RELEVANCE OF LABORATORY FINDINGS TO THE BIGHORN RIVER

Application of laboratory findings to the Bighorn River is complicated by an array of factors. The most obvious factors are the relatively constant supersaturation levels provided by our supersaturating system and the inability of juvenile brown and rainbow trout to compensate for high gas levels by depth selection in laboratory tanks. Nevertheless, information pertaining to Bighorn River salmonid species composition, juvenile survival, population genetics, and indirect mortality due to GBT was obtained.

Differences in physiological susceptibility of adult brown and rainbow trout to gas supersaturated water could be responsible for the imbalance in species composition present in the Bighorn River. My data showed that differences in 30-d mortality between species diminished with increasing fish size. There is probably little difference in the physiological ability of adult brown and rainbow trout to survive high levels of supersaturation. Any differences in spawning success in the Bighorn River may be related to higher gas levels during rainbow trout spawning.

Physiological differences in susceptibility of brown and rainbow trout fry to GBT may also account for the relatively low numbers of rainbow trout present in the Bighorn River, especially since rainbow fry emerge from the gravel in late spring to early summer when gas levels are reaching an annual peak. However, my tests showed that juvenile rainbow trout at swim-up size can tolerate 125% supersaturation with limited mortality. Also, in all comparisons juvenile brown trout were more susceptible to supersaturation of dissolved gases than rainbow trout of similar size. This information implies that the rainbow trout production may not be limited by direct GBT mortality during early juvenile rearing.

Gas levels in the Bighorn River fluctuate during juvenile rearing and throughout maturation. My attempts to approximate this situation during recovery and repeated exposure tests showed that both juvenile brown and rainbow trout can recover from GBT given adequate time, but subsequent exposures can lead to increased symptom severity. Furthermore, juvenile brown and rainbow trout did not acclimate to gas supersaturated water. Less tolerant individuals in the Bighorn River may be dying early, limiting survival to sexual maturity to tolerant trout. Genetic selection favoring tolerant fish may be occurring in the Bighorn River below Yellowtail Afterbay Dam.

Tolerance to gas supersaturated water alone may not guarantee juvenile trout survival. Predation tests in the experimental channel indicated that in some instances juvenile brown trout with GBT may be more susceptible to predation. I also found that juvenile brown trout capable of tolerating three 120-h exposures to 118% supersaturation, given 30-d to recover in between, still formed emphysema.

Results from my disease study indicated that emphysema could provide a direct pathway for bacterial infection resulting in mortality indirectly related to exposure to gas supersaturated Bighorn River water.

SUMMARY

1. The critical threshold required to cause acute mortality in juvenile rainbow and brown trout (53.1 - 130.5mm) appears to be between 113 - 117 percent TGP.

2. Length and weight of juvenile brown and rainbow trout had a significant influence on susceptibility to supersaturated water. During early tests intra-specific percent cumulative mortality for both species exposed to the high gas treatment was significantly less than during later tests when fish were larger.

3. The frequency of emphysema occurrence on certain regions of the body varied with fish size.

4. Daily mortality of brown trout exposed to high gas supersaturation levels (125%) was significantly greater than that of rainbow trout of similar size during all comparisons. The difference in susceptibility was most evident when fish were smallest (0.4 g). Differences in percent cumulative mortality between species were less in subsequent tests when fish were larger (8.3 - 60.5 g).

5. Juvenile brown trout surviving exposure to 112% supersaturation were more prone to external symptoms of GBT than juvenile rainbow trout of similar size.

6. Juvenile rainbow and brown trout recovery from GBT varied with external symptom severity. Fish of both species with less severe symptoms recovered more often than fish with more severe symptoms.

7. Non-recovering fish exhibited eye damage characterized by severe unilateral and bilateral exopthalmia, hemorrhaging, cloudiness or cataracts of the cornea, or bubbles in the orbit of the eye.

8. The condition of fish subjected to intermittent exposure worsened with each exposure leading to poorer recovery. The development of new symptoms with each exposure and recurrence and progression of prior

symptoms was responsible for poorer recovery with each additional exposure.

9. Some fish may become sensitized to GBT, while other individuals may be tolerant to exposure to gas supersaturated water.

10. Exposure to 112 % gas supersaturated water did not affect growth of juvenile brown and rainbow trout.

11. Predation tests in circular tanks showed no difference in predation vulnerability between juvenile brown and rainbow trout exposed and non-exposed to gas supersaturated water.

12. Predation tests in an experimental stream showed that brown trout exposed to 118% gas supersaturated water for 5-d were more vulnerable to predation. There was no statistically significant selective predation on brown trout exposed for 4, 6, or 7 days, nor on rainbow trout exposed for 11 to 12 days.

13. Bacterial challenges indicated that GBT may increase the susceptibility of brown trout to A. hydrophila infection.

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